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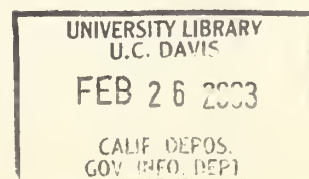
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**SPECIAL PUBLICATION 124**

**GUIDELINES FOR GEOLOGIC  
INVESTIGATIONS OF NATURALLY  
OCCURRING ASBESTOS IN CALIFORNIA**

**2002**



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## SPECIAL PUBLICATION 124

# GUIDELINES FOR GEOLOGIC INVESTIGATIONS OF NATURALLY OCCURRING ASBESTOS IN CALIFORNIA

EDITED BY

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Copies of these Guidelines and other related information are available on the World Wide Web at <http://www.consrv.ca.gov>. Copies are also available for purchase from the Public Information Offices of the California Geological Survey.


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## INTRODUCTION

California has experienced a rising concern over potential public exposure to naturally occurring asbestos (NOA) in recent years. Consequently, geologists in California are increasingly called upon to evaluate the NOA potential of property prior to land-use decisions, land acquisition, or property development. As new NOA regulations are enacted that affect activities such as excavation and grading in areas where NOA may be present, geologic information will be an important component of the regulatory decision-making process. Geologic information may also be useful in designing site development to avoid potential long term exposure to NOA or in developing monitoring or mitigation plans to minimize potential short term NOA exposures during construction activities.

The term “asbestos” has different definitions in common, regulatory, and mineralogical usage, and these definitions are discussed in more detail in the Background and Mineralogy of Asbestos sections. As it is commonly used, asbestos is a commercial term for the asbestiform crystal habits of six naturally occurring minerals. The six types of asbestos are chrysotile, crocidolite (asbestiform riebeckite), amosite (asbestiform cummingtonite-grunerite), asbestiform tremolite, asbestiform actinolite, and asbestiform anthophyllite. The various asbestos minerals have properties that have made these minerals useful in many manufactured products and industrial processes. Naturally occurring asbestos, or NOA, is the term applied to the natural geologic occurrence of any of the six types of asbestos minerals.

Medical studies have shown there is a connection between certain diseases (asbestosis, lung cancer, and mesothelioma) and asbestos exposure. Asbestos is now classified as a known human carcinogen by state, federal, and international agencies and all six types of asbestos are considered hazardous. Due to health concerns related to asbestos exposure, the use of asbestos in manufactured goods and processes in the United States has decreased over the last 30 years.

Because the asbestos minerals are naturally occurring, and may be present in a variety of geologic environments, concern has been raised over possible environmental exposure of the public to asbestos minerals in California. Although only the six commercial asbestos minerals are currently regulated, other naturally occurring asbestiform minerals that are suspected of similar health effects may be regulated in the future. Some other asbestiform minerals are discussed in the section on the Mineralogy of Asbestos. Geologists should be aware of other asbestiform minerals, as well as their current regulatory status, when conducting NOA investigations.

### Scope

These guidelines have been developed as a starting point for geologists involved in conducting or reviewing NOA investigations. A geologist may be called upon to assess the potential for NOA at sites having widely varying degrees of development, disturbance, and prior geologic observation. These guidelines describe general procedures for use by geologists to conduct site investigations for NOA and, while they do not constitute a complete listing of all techniques used in such studies, they do attempt to include all major topics. Investigations for NOA may be conducted for projects ranging in size from a single lot to a large acreage master plan. Investigations may vary in scope from a single-family dwelling to large residential, commercial, or industrial developments, or to public works projects including highway construction or roadway improvements. The purpose, scope, and methods of investigation used in evaluating NOA will vary depending on conditions at specific sites and the nature of the proposed project or development.



The scope of the investigation and the nature of the report may vary based on guidelines or review criteria of agencies or organizations having regulatory responsibility. In some projects, determination that a site contains potentially asbestos-containing materials such as serpentinite or ultramafic rock may be adequate, while in other cases it may be necessary to define the type, distribution, and amount of asbestos minerals at the site. For a given site, some topics may be addressed in more detail than at other sites because of differences in geologic setting or site conditions. Conclusions resulting from an initial assessment of NOA potential on a site should be confirmed, or modified, by taking advantage of later opportunities to observe and sample as the site goes under construction, unless the initial observations can preclude the possibility of encountering NOA during site development. The geologist performing or supervising each investigation has a responsibility to determine what is appropriate and necessary in each case, as does the geologist who reviews each report.

These Guidelines discuss a variety of topics and methods that may be useful in any geologic study or review related to NOA. Additional methods and approaches to investigating NOA sites may be developed in the future. If other methods are used, they should be justified with appropriate data and documentation. If the investigation is being conducted in response to a regulatory requirement, the geologist should check with the regulating agency to find out what methods (particularly sampling and analytical methods) and procedures are acceptable to meet the requirements of that agency.

NOA reports, as contemplated by these Guidelines, are professional geologic reports and therefore the work of preparing, or supervising the preparation of, a NOA report falls under the purview of the Geologist and Geophysicist Act (Business and Professional Code, Chapter 12.5). Geologic reports, such as NOA reports, which fall within the scope of the Act must be prepared by or under the direct supervision of a California Registered Geologist practicing in his or her area(s) of expertise. Geologic reports and maps produced for projects where geologic factors affect planning, design, construction or maintenance of civil engineering works should preferably be prepared by or under the direct supervision of a Certified Engineering Geologist. Geologic reports and maps prepared for projects where the occurrence, distribution, quantity, quality, and movement of ground water is of primary significance to the report's findings should preferably be prepared by or under the direct supervision of a Certified Hydrogeologist. If a report contains significant geophysical information, it should be co-signed by a California Registered Geophysicist, or the signed geophysical report may be appended to the geological report. Additional references for preparing and reviewing other types of geological reports are included in the reference section of these Guidelines.

A NOA report may be a stand-alone report or may be combined with other geologic or environmental reports such as Natural Hazards Disclosure Reports, an engineering geology site assessment, or an engineering geology design-level report. A NOA report should reference any Phase I or Phase II environmental site investigations available for the site.

## **Limitations**

These Guidelines are intended for use by geologists performing or reviewing NOA investigations and are not intended to provide guidance to the layperson in evaluating or interpreting geologic reports on NOA. These Guidelines are informational in nature and are not regulations. The Guidelines have no force of law and do not set standards of practice. These Guidelines discuss a scope of work and suggest a format for reports. They do not include a complete listing of techniques or topics, nor should all techniques described be used or all topics listed be addressed in every project. These Guidelines are not intended to be applied to economic geology studies, occupational health studies, or forensic studies. Such studies require specialized techniques or methodologies that are beyond the scope of these Guidelines.

## BACKGROUND INFORMATION

### Introduction

A comprehensive review of the health effects and regulation of asbestos is beyond the scope of these guidelines. However, a brief summary may help the geologist involved in NOA investigations to understand the complexity of these issues. The term “asbestos” has different definitions in mineralogical, commercial, and regulatory usage, and it is important that the geologist investigating NOA be aware of these different definitions and when they may apply (e.g., National Research Council, 1984; Skinner and others, 1988). The commercial and regulatory definitions of asbestos will be discussed below, followed by a brief review of issues related to asbestos exposure. The mineralogical definition will be discussed in more detail in the section on The Mineralogy of Asbestos.

### Commercial Definitions

The term asbestos is used to identify a group of six commercially important silicate minerals of fibrous or asbestiform habit having properties of high tensile strength, flexibility, chemical resistance, and heat resistance. These properties have made these minerals useful in many manufactured products and industrial processes during the twentieth century. A few examples of the many uses of asbestos include brake and clutch linings, insulation, textiles, and filtration products.

The six types of asbestos are chrysotile, crocidolite (asbestiform riebeckite), amosite (asbestiform cummingtonite-grunerite), asbestiform tremolite, asbestiform actinolite, and asbestiform anthophyllite. The terms “crocidolite” and “amosite” are varietal or trade names rather than formal mineral names. However, they are common in the literature regarding the regulation and health effects of asbestos and, as described below, have been incorporated in regulatory terminology. Chrysotile (also called white asbestos) has been, and is, the most commonly used type of asbestos and probably accounts for 90% to 95% of the worldwide historic asbestos production. Crocidolite (blue asbestos), and amosite (brown asbestos) make up most of the rest of the world’s historic production but small amounts of anthophyllite-asbestos, tremolite-asbestos, and actinolite-asbestos have also been produced (Ross, 1981; Ross and Virta, 2001). Currently, only chrysotile is commercially important and Canada is the world’s leading producer. Historically, California has produced chrysotile, tremolite-asbestos, and possibly some anthophyllite-asbestos.

### Regulation and Regulatory Definitions

The regulation of asbestos initially resulted from concern over the health and safety of workers subject to occupational exposure to asbestos. The industries involved with the mining, milling, manufacturing, and installation of asbestos products were the focus of this initial concern. Subsequently other regulations have been enacted that affect areas other than worker health and safety. According to Vu (1993):

“Regulations and guidelines have been established by the various regulatory authorities in the U.S.: (1) to limit exposure to asbestos in the workplace; (2) to minimize emissions of asbestos into the atmosphere from activities involving the milling, manufacturing, and processing of asbestos, demolition and renovation of asbestos-containing buildings, and



the handling and disposal of asbestos-containing waste materials; (3) to control asbestos-containing materials in schools and in buildings; (4) to limit the level of asbestos in ambient water and drinking water; and (5) to restrict or to prohibit the use of asbestos in certain products and applications.”

In California, regulations have been implemented to protect the public from exposure to naturally occurring asbestos. The California Air Resources Board (CARB) has identified asbestos [in the asbestiform habit of the following minerals: chrysotile (fibrous serpentine), crocidolite (fibrous riebeckite), amosite (fibrous cummingtonite-grunerite), fibrous tremolite, fibrous actinolite, and fibrous anthophyllite] as a toxic air contaminant. In doing so, the CARB identified all asbestos fibers, irrespective of length, with an aspect ratio greater than or equal to 3, equally hazardous to public health (Department of Health Services, 1986). In 1990, the CARB adopted an asbestos Airborne Toxic Control Measure (ATCM) that restricted the use of serpentine aggregate for surfacing applications to materials that contained less than 5% asbestos as determined by CARB Method 435. In July 2000, the CARB adopted amendments to this ATCM that added ultramafic rock and lowered the threshold asbestos content to less than 0.25% as determined by CARB Method 435. In July 2001, the CARB adopted an additional asbestos ATCM for construction, grading, quarrying, and surface mining operations. This ATCM will regulate grading and excavation activities to minimize associated dust generation in areas of serpentinite/ultramafic rock, which commonly contain asbestos. A brief summary of selected current asbestos regulations can be found in Appendix A.

For federal regulatory purposes, the United States Occupational Safety and Health Administration (OSHA) has defined asbestos as follows (29 CFR, 1910.1001, subpart Z(b)):

“Asbestos” includes chrysotile, amosite, crocidolite, tremolite asbestos, anthophyllite asbestos, actinolite asbestos, and any of these minerals that have been chemically treated and/or altered.

Additionally, OSHA has defined the term “fiber” as follows:

“Fiber” means a particulate form of asbestos 5 micrometers or longer, with a length to diameter ratio of at least 3 to 1 (29 CFR, 1910.1001, subpart Z(b)).

These definitions are regulatory definitions and not mineralogical definitions. Other naturally occurring asbestiform minerals are not included in these definitions. These include other types of amphibole-asbestos such as winchite-asbestos and minerals such as erionite (a zeolite) that are suspected or known to pose a health risk similar to the regulated asbestos minerals (Wylie and Verkouteren, 2000; Ross and others, 1993). As more information on the health effects of other asbestiform minerals becomes available, new regulations may be developed, or existing regulations modified, to include asbestiform minerals other than those currently regulated. It will also be apparent to the geologist/mineralogist that these definitions do not clearly distinguish between fibers and cleavage fragments. Some in the mineralogical community (Skinner and others, 1988; Addison, 2001) have recommended modification of the regulatory definitions discussed above. However, at the present time these recommendations have not been adopted by any of the agencies with regulatory authority over asbestos issues in California. Geologists involved in NOA investigations should always be aware of the current asbestos definitions and analytical requirements of any reviewing or regulatory agency.

## Health Effects of Asbestos

Medical studies have shown there is an association between certain diseases and asbestos exposure. Exposure to asbestos fibers is associated with the following diseases: asbestosis - a diffuse fibrous scarring of the lungs; pleural plaques – localized fibrous scars lining the space surrounding the lungs; diffuse malignant mesothelioma - rare malignant tumors arising from the pleural, pericardial, or peritoneal linings; and bronchogenic carcinoma – lung cancer (Kane, 1993).

Initial concern over the health effects of asbestos arose from studies of workers in the asbestos related industries and much of the medical data on asbestos related diseases come from these occupational studies. Because the studies were of workers in the asbestos industries, the asbestos minerals they had been exposed to were the six minerals commonly used in the industry. Since the initial studies of occupational asbestos exposure, other studies have investigated non-occupational exposures to asbestos minerals and the potential health effects of other mineral fibers. A review of the health effects of many mineral dusts and fibers, including asbestos, can be found in Guthrie (1992), and Guthrie and Mossman (1993). Specific information on the health effects of asbestos can be found in the *Toxicological Profile for Asbestos by the Agency for Toxic Substances and Disease Control* (2001).

While the processes by which the asbestos minerals cause lung cancer and mesothelioma have been studied, no general consensus has been reached by the medical community regarding the exact mechanism, or combination of mechanisms, by which these materials cause these diseases. There is also not a general consensus among the medical community about the potency of different fiber sizes, relative potency of different asbestos species, and potential health effects of cleavage fragments vs. fibers. Some of these issues are controversial, and this contributes to the overall complexity of the asbestos issue. Geologists should be aware that asbestos is presently classified as a known human carcinogen by state, federal, and international agencies. Currently, all six of the commonly used types of asbestos are considered to be hazardous by federal and California regulatory agencies.

## **SUGGESTED CONTENT FOR GEOLOGIC REPORTS ON NATURALLY OCCURRING ASBESTOS**

Guidelines for suggested report contents for a variety of different types of geologic investigations have been published previously by the California Department of Conservation, Division of Mines and Geology (now known as the California Geological Survey) (2001, 1998, 1986a, 1986b) and the California Department of Consumer Affairs, Board for Geologists and Geophysicists (1998a, 1998b, 1998c, 1998d). This outline is derived from the previously published guidelines but has been modified to be more specific to investigations of NOA.

The following topics should be considered and addressed in detail where essential to support opinions, conclusions, and recommendations in any geologic report on NOA. It is not expected that all of the topics or investigative methods would be necessary in a single investigation. Clear descriptions of work and unambiguous presentation of results are encouraged. It is important for reports that present conclusions or recommendations based, in part, on field sampling or field or laboratory analysis to include the analytical results with adequate descriptions of the methods employed. Specific reference to standard sampling, sample preparation, and analytical methods should be made where appropriate. Where necessary, technical terms should be defined.

### **Text**

- A. **Introduction:** The introduction should present a clear and complete statement of the purpose of the report and the work undertaken, including limitations regarding the scope, level of study, and methods used. The introduction may include the location of the project (latitude-longitude and legal, street address, or other description), and a location map showing where the site is in relation to landmarks, topographic features, etc. The introduction may include a description of the proposed or existing site use, and past site uses. The time frame of the work and statements regarding authorization and confidentiality requirements may also be included. The introduction may also include contact information for property owners and/or their agents and should identify the party commissioning the report and the intended purpose of the report.
- B. **Regional Geologic Setting:** This section may include reference to geologic province and location of major structural features or geologic units that could influence the presence or distribution of asbestos minerals on the site. Information and data that are the foundation for the present study should be discussed in some detail and referenced appropriately.
- C. **Site Description and Conditions:** This section describes the site and site conditions including information on geologic units, soils, landforms, graded and filled areas, vegetation, existing structures, etc., that may affect the choice of investigative methods and the interpretation of the data.
- D. **Methods of Investigation:**
  - I. Review of published and unpublished literature, maps and records concerning geologic units, soils, structural features, mineralization, etc.



2. Interpretation of aerial photography or other remote sensing information to detect rock, soil, or vegetation contrasts or structural features that may indicate or influence the presence or distribution of asbestos minerals.
  3. Surface observations, including mapping of geologic and soils units, structural features, and zones of alteration or mineralization.
  4. Subsurface investigations.
    - a. Trenching and other excavations to permit detailed and direct observation of continuously exposed geologic units, soils, and structures: must be of adequate depth and carefully logged.
    - b. Borings and test pits to permit collection of data on geologic units at specific locations. Data points must be sufficient in number and spaced adequately to permit valid correlations and interpretations.
    - c. Geophysical investigations used to define the subsurface extent of potentially asbestos bearing rock units.
    - d. Other methods or sample sources.
  5. Sampling and analytical methods used in determining the lithology or mineralogy of geologic materials or soils need to be described, along with their limitations. If standard sampling, sample preparation, or analytical methods (such as ASTM or EPA methods) have been used they should be documented and referenced. Project and laboratory Chain of Custody and Quality Assurance / Quality Control (QA/QC) procedures should be described. Laboratory certification should be noted.
  6. It is important that methods of reducing and interpreting data from borings, test pits, geophysical surveys, and mineralogical analyses be explained and appropriate illustrations and references provided.
- E. Results of Investigation: Describes the results of the investigation performed and summarizes the analytical results.
- F. Conclusions: Discusses the presence or absence of asbestos minerals or potentially asbestos-containing rock or soil, and the concentration and distribution of these materials at the site. Include a statement of the degree of confidence in and limitations of the data and conclusions.
- G. Recommendations: Recommendations should be clearly separated from conclusions because recommendations are not totally dependent on geologic factors. Recommendations may include placement of structures to best take advantage of geologic conditions or other recommendations as appropriate for the proposed project.

## References

- A. Literature and records cited or reviewed; citations should be complete.
- B. Aerial photographs or other images interpreted – list type, date, scale, source, and index numbers.
- C. Other sources of information including well records, personal communications, and other data sources.

## Illustrations

- A. Location map – identify site locality, geographic features, or major regional geologic features, and other pertinent data.
- B. Site development map – at an appropriate scale to show site boundaries, existing and proposed structures, excavations, graded areas, streets, and locations of exploratory trenches, borings, sample locations, geophysical traverses, and other data.
- C. Geologic map (on topographic or planimetric base at appropriate scale – typically 1:24,000 or larger) to show the distribution of geologic and soils units, structural features, zones of alteration or mineralization, etc. May be combined with the site development map. Geologic maps should include the dates of geologic fieldwork and the name and license number of the responsible geologist.
- D. Maps should include adequate information on data sources, dates of survey or aerial photography, reference datum, scale, contour interval, orientation, and geographic coordinate system used.
- E. Geologic cross sections, if needed, illustrating significant or appropriate geologic features in the third dimension. The limits of any proposed excavations should be shown on cross sections.
- F. All maps and cross sections should have appropriate titles, scales, and legends.
- G. Site or feature photographs.
- H. Illustrations of analytical results, photographs of thin sections, SEM images, etc.
- I. Logs of exploratory borings, test pits, or trenches showing the details of observed features and conditions.
- J. Geophysical data and the geologic interpretation of those data (if geophysical methods were used).
- K. Other illustrations, as appropriate.



**Supporting Data Not Already Provided**

Petrographic analyses, laboratory analyses, Chain of Custody documentation, QA/QC information, or other information needed to support the conclusions reached in the report.

**Signature of Professional in Responsible Charge**

The California Business and Professions Code requires that a Registered Geologist, and/or Certified Engineering Geologist, or Certified Hydrogeologist shall exercise and maintain responsible charge and shall certify geologic reports and must be working within his/her area of expertise. Inclusion of license numbers and/or stamps shall be in accordance with the requirements of the licensing board, local government or other applicable regulatory requirements.

## THE MINERALOGY OF ASBESTOS

### Introduction

It is important that the geologist be aware of the definitions being used by any potential regulatory or reviewing agency when preparing NOA reports. The usage of these terms often varies among geologists, regulators, and health professionals who study asbestos. Discussions of the use of mineralogical terminology for fibrous materials, particularly asbestos, and problems that have arisen from improper or inconsistent usage can be found in Zoltai (1981). This section presents the mineralogical definitions for some of the terms needed for NOA studies. The mineralogy of the asbestos minerals (Table 1) is briefly reviewed with emphasis on the serpentine and amphibole mineral groups. A brief discussion of other non-serpentine and non-amphibole fibrous minerals is also included.

Table 1 – The Regulated Asbestos Minerals

Regulatory Name	Mineral Name	Mineral Group	Ideal Chemical Formula
Chrysotile	Chrysotile	Serpentine	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$
Tremolite	Tremolite	Amphibole	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Actinolite	Actinolite	Amphibole	$\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Anthophyllite	Anthophyllite	Amphibole	$\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Crocidolite	Riebeckite	Amphibole	$\text{Na}_2(\text{Fe}^{2+}_3, \text{Fe}^{3+}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$
Amosite	Cummingtonite-Grunerite	Amphibole	$\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2 - \text{Fe}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

“Asbestos” is a commercial term rather than a mineralogical term and does not define a particular mineral species or mineral group. In mineralogy, the term “asbestiform” (defined below) is used to describe a specific type of mineral fibrosity in which the fibers possess high tensile strength and flexibility. The terms “asbestos” and “asbestiform” are sometimes used synonymously but this is not correct. The term asbestiform may be applied to minerals other than the commercial asbestos minerals if they crystallize in the asbestiform habit.

### Definitions of Descriptive Terms

**HABIT** is the actual shape assumed by a crystal or aggregate of crystals, and the terms used to describe the particular habits of minerals and mineral aggregates can be found in many mineralogy texts (e.g., Zoltai and Stout, 1984; Klein and Hurlbut, 1993). These terms can be used to describe habit at any scale, from centimeters in a hand specimen down to fractions of a micron under the electron microscope. Habit does not imply either a particular crystal structure or chemical composition. Many minerals, including the asbestos minerals, crystallize in a variety of habits depending on the environment in which the mineral forms. Therefore, habit alone cannot be used to identify a mineral.

**FIBROUS** (National Research Council, 1984) refers to “(1) single crystals that resemble organic fibers such as hair or cotton and (2) large crystals or crystalline aggregates that look like they are composed of fibers (i.e., long, thin, needlelike elements) (Dana and Ford, 1932). The apparent fibers do not need to be separable. If the fibers are separable and are strong and flexible, they are asbestiform. If they have the normal strength and brittleness of the mineral, they are acicular.”

The terms “apparently fibrous” or “pseudofibrous” are sometimes applied to single crystals or polycrystalline aggregates that have a fibrous appearance but are not composed of separable fibers. In such cases, the fibrous appearance may be the result of oscillatory crystal growth, twinning, or pseudomorphic replacement of another fibrous mineral.

**ASBESTIFORM** (National Research Council, 1984) refers to “the unusual crystallization habit of a mineral when the crystals are thin, hair like fibers. Historically, the definition of asbestiform habit was based primarily on appearance, and the properties were only implied. At present, the definition of asbestiform habit is often augmented to include a statement on the properties of asbestiform fibers, i.e., shape; enhanced strength, flexibility, and durability; diameter-dependent strength; and unique surfaces. The fibers of asbestos are good examples of the asbestiform habit.”

In these guidelines, “asbestiform” refers to the crystallization habit of a mineral where the crystals are thin, hair like fibers, with unique properties as mentioned above. The term “fibrous” is a broad term that refers to fibrous appearing crystals without any implication regarding the special properties implied by the term asbestiform. Asbestiform describes a special type of fibrosity. Asbestiform minerals are fibrous but not all fibrous minerals are asbestiform.

**ACICULAR** (National Research Council, 1984) refers to “crystals that are extremely long and thin and have a small diameter. (An acicular crystal is a special type of prismatic crystal. A prismatic crystal has one elongated dimension and two other dimensions that are approximately equal.) As defined by the American Geological Institute (1980), a mineral fragment must be at least three times as long as it is wide to be called acicular. Acicular crystals or fragments are not expected to have the strength, flexibility, or other properties of asbestiform fibers.”

**CLEAVAGE FRAGMENTS** are mineral fragments bounded by cleavage planes. Cleavage refers to the preferential splitting of crystals along planes of structural weakness (cleavage planes). Minerals with one cleavage plane produce platy fragments, minerals with two distinct cleavage planes will produce prismatic or acicular fragments, and minerals with three or more cleavage planes form polyhedral fragments. The strength and flexibility of cleavage fragments are approximately the same as those of the crystals from which they are derived. Cleavage cannot produce the high strength and flexibility of asbestiform fibers.

How geologists use the terms asbestiform, fibrous, acicular, and cleavage fragment, is dependent on their individual training and experience. The situation is further complicated because many mineral species can crystallize in more than one habit, depending on the conditions in which they grow. Tremolite, for example, can crystallize in prismatic, acicular, fibrous, or asbestiform habits. Additionally, both cleavage fragments and fibers of tremolite might be called acicular or fibrous, depending on the individual making the observation. However, cleavage fragments can be distinguished from fibers under the microscope by their tendency to form fragments with stepped



sides and relatively small length to width ratios. Furthermore, fiber “bundles” in asbestiform minerals commonly exhibit splayed ends, in which fibers show some separation from adjoining fibers. Cleavage fragments do not display splayed ends (Langer and others, 1991; Wylie, 1990).

The use of these terms becomes even more problematic when discussing crystal habit in thin sections where the distinction between asbestiform, fibrous, and acicular habits is difficult to discern because of the thickness and 2-dimensional nature of the thin section.

### **Mineral Species, Groups, and Mineral Identification**

Mineral species are defined by their internal crystal structure and chemical composition. Mineral species with closely related structures and compositions may be considered “groups.” Variations in the chemical composition of minerals within a group may reflect secondary features of the crystal structure, such as different site occupancies due to differing cation sizes. Most mineral properties, such as color, luster, crystal habit, hardness, cleavage, etc., result from these two characteristics (crystal structure and chemical composition) and chemical and physical conditions at the time of mineral formation. Geologists are trained to identify minerals in the field using these properties. However, these properties are not always uniquely diagnostic of a mineral species and this is particularly true for asbestos and asbestiform minerals that may be encountered during a NOA investigation. Therefore, field identification of asbestos minerals should be considered provisional until verified by laboratory analysis. Ultimately, determination of crystal structure and chemical composition is necessary to unequivocally identify any mineral species, and this requires laboratory analysis. Crystal structures are commonly determined by X-ray or electron diffraction techniques, and chemical composition can be determined either by classical chemical analysis or by a variety of instrumental methods. Variations in the optical properties of minerals related to crystal structure and chemical composition can be measured with the polarized light microscope. Some of these techniques, which may be applicable to NOA investigations, are discussed in the section on Analytical Methods.

### **The Serpentine Mineral Group**

The serpentine group (Table 2) consists of several species that share a common crystal structure. This discussion will concentrate on the rock-forming magnesium-rich serpentine minerals—lizardite, chrysotile, and antigorite. These three minerals are sometimes referred to collectively as “serpentine” and are important constituents of the rock serpentinite. The other members of the serpentine group listed in Table 2 occur much less commonly and are not discussed in these Guidelines. General information on the physical and chemical properties of individual species that make up the serpentine group is available in Gaines and others (1997) and Anthony and others (1995). For more detailed discussions of these minerals see Wicks (1979), Wicks and O’Hanley (1988), Veblen and Wylie (1993), and O’Hanley (1996).

Table 2 - The Serpentine Group Minerals<sup>1</sup>

Mineral Name <sup>2</sup>	Formula
Antigorite <sup>3</sup>	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$
Lizardite	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$
Chrysotile <sup>4</sup>	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$
Caryophilite	$(\text{Mn}^{2+}, \text{Mg})_3\text{Si}_2\text{O}_5(\text{OH})_4$
Nepouite	$\text{Ni}_3\text{Si}_2\text{O}_5(\text{OH})_4$
Greenalite <sup>3</sup>	$(\text{Fe}^{2+}, \text{Fe}^{3+})_{2,3}\text{Si}_2\text{O}_5(\text{OH})_4$
Amesite	$\text{Mg}_2\text{Al}(\text{Si}, \text{Al})\text{O}_5(\text{OH})_4$
Berthierine	$(\text{Fe}^{2+}, \text{Fe}^{3+}, \text{Al}, \text{Mg})_{2,3}\text{Al}(\text{Si}, \text{Al})_2\text{O}_5(\text{OH})_4$
Brindleyite	$(\text{Ni}, \text{Mg}, \text{Fe}^{2+})_2\text{Al}(\text{Si}, \text{Al})\text{O}_5(\text{OH})_4$
Fraipontite	$(\text{Zn}, \text{Al})_3(\text{Si}, \text{Al})_2\text{O}_5(\text{OH})_4$
Kellyite	$(\text{Mn}^{2+}, \text{Mg}, \text{Al})_3(\text{Si}, \text{Al})\text{O}_5(\text{OH})_4$
Manandonite	$\text{Li}_2\text{Al}_4(\text{Si}_2\text{AlB})\text{O}_{10}(\text{OH})_8$
Cronstedtite	$\text{Fe}^{2+}_2\text{Fe}^{3+}(\text{Si}, \text{Fe}^{3+})\text{O}_5(\text{OH})_4$
Pecoraite	$\text{Ni}_3\text{Si}_2\text{O}_5(\text{OH})_4$

<sup>1</sup>Carlosturanite,  $(\text{Mg}, \text{Fe}^{2+}, \text{Ti})_{21}(\text{Si}, \text{Al})_{12}\text{O}_{28}(\text{OH})_{34} \cdot \text{H}_2\text{O}$ , is a closely related species that may be asbestiform and may occur in the same geologic setting as chrysotile.

<sup>2</sup>The rock forming serpentine minerals are highlighted in **bold**.

<sup>3</sup>The formulas given for antigorite and greenalite slightly overstate the amounts of Fe, Mg, and OH in these minerals.

<sup>4</sup>Some modern mineralogy texts refer to chrysotile as a sub-group, which contains the polytypes clinochrysotile and orthochrysotile and the polymorph parachrysotile, rather than as a mineral species. The various polytypes and polymorphs of chrysotile, and the specialized X-ray diffraction techniques required to study them are discussed in Wicks and O'Hanley (1988). In these Guidelines, it is not necessary to distinguish between the various polytypes or polymorphs, and chrysotile is used herein as a generic term.

Serpentine minerals are phyllosilicates ("sheet" or "layer" silicates). The basic structural unit of the serpentine minerals is a layer made of one tetrahedral sheet bonded to one octahedral sheet (Figure 1). In the tetrahedral sheet, the tetrahedra are composed of four oxygen atoms surrounding a silicon atom. The silica tetrahedra share three basal oxygen atoms with adjacent tetrahedra and are arranged in hexagonal rings that form a continuous sheet. The fourth apical oxygen atoms in the silica tetrahedra, which are not shared with adjacent tetrahedra, are all oriented in the same direction and shared with the octahedral layer. Octahedra are composed of six oxygen and hydroxyl ions that surround a magnesium atom and are shared with adjacent octahedra to form a continuous sheet. The tetrahedral and octahedral layers are linked by sharing of oxygen atoms, forming a two-layer structure having the ideal formula  $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ . There is limited chemical substitution in the Mg-serpentine minerals because only small amounts of a few other elements, principally iron and aluminum, can fit into sites in the structure where magnesium or silica normally reside.

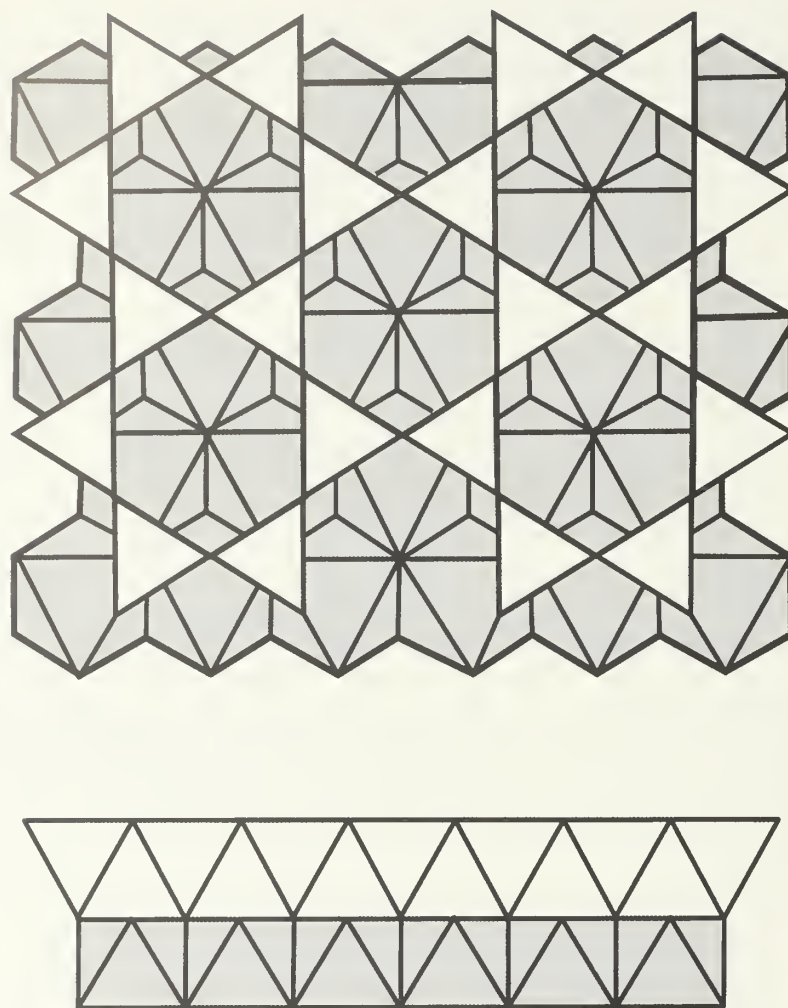


Figure 1. The basic structural unit of the serpentine group minerals antigorite, chrysotile, and lizardite consists of one tetrahedral sheet bonded to one octahedral sheet. The octahedral sheet is shaded in the plan and end views above. Modified from Veblen and Wylie, 1993.

The dimensions of an ideal (non-distorted) magnesium-occupied octahedral sheet and an ideal silicon-occupied tetrahedral sheet are slightly different. This difference results in a misfit between the tetrahedral and octahedral sheets that must be accommodated in some fashion for the serpentine tetrahedral-octahedral (t-o) layer to be stable. There are three common ways in which this structural “accommodation” occurs, with the resulting structures being represented by the three serpentine minerals—lizardite, chrysotile and antigorite. In lizardite, the misfit is accommodated by slight in-plane rotation of the tetrahedra within the planar structure of the layer. Chrysotile accommodates the misfit by the curling of the t-o layer into scrolls or hollow cylinders. In antigorite, alternating segments of curved layers are periodically inverted to create a wave-like or corrugated structure that accommodates the misfit (Figure 2).



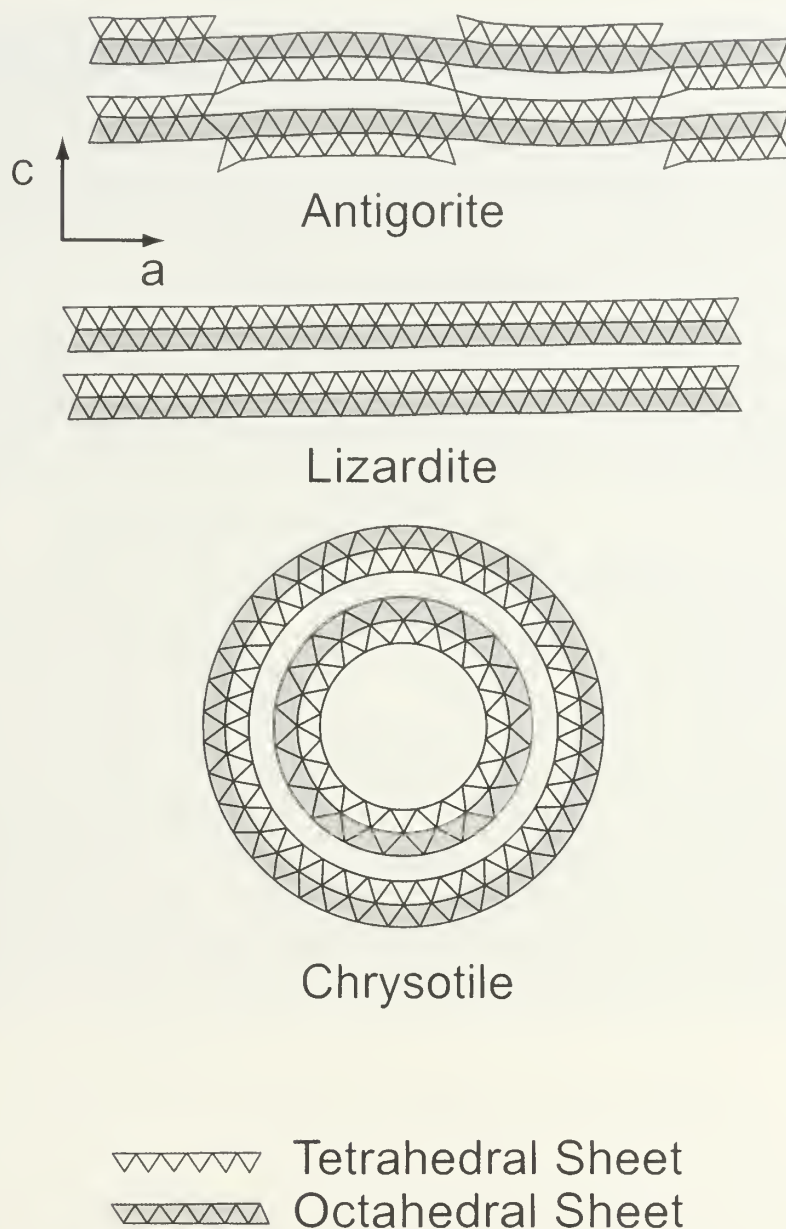


Figure 2. Simplified diagrams of the structures found in antigorite, lizardite, and chrysotile. Antigorite has a corrugated structure created by periodic inversions of the t-o sheets. Lizardite has a planar structure. Asbestiform chrysotile has a structure in which the t-o layers are curved into cylinders as shown above, or spirals (scrolls). Modified from Livi and Veblen, 1987.

Lizardite is the most abundant serpentine mineral (Wicks and O'Hanley, 1988). The misfit between the t-o sheets in the lizardite layer is relieved by in-plane rotation of the tetrahedra in the t-sheet, resulting in a planar structure for the lizardite layer. Additionally, minor substitution of Al or  $\text{Fe}^{3+}$  into the sheets may further stabilize the planar structure of the lizardite layer. Although the lizardite layer is planar (Figure 3), it may exhibit some curvature, particularly near the edge of the layer. Lizardite commonly occurs as massive or scaly aggregates and has not been found in the asbestiform habit. The range of chemical compositions for lizardite overlaps those for chrysotile.



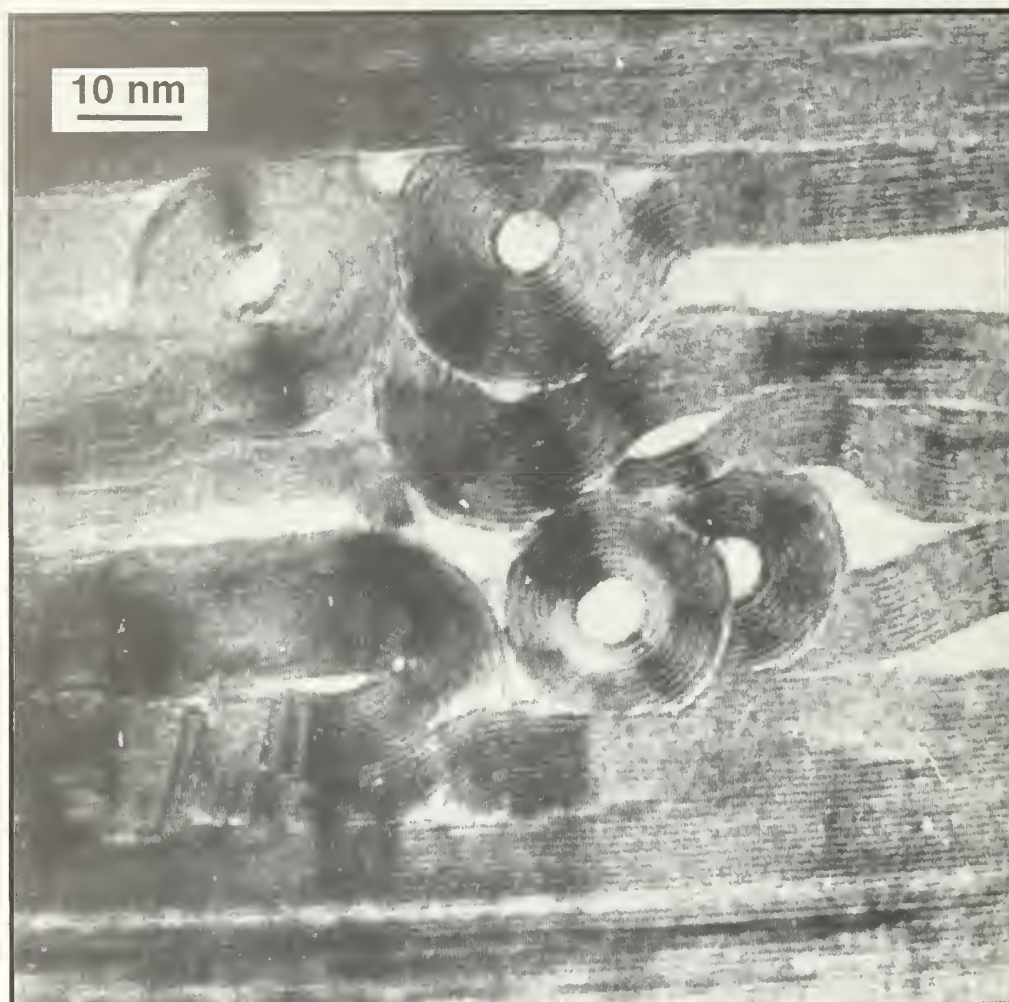


Figure 3: TEM image of lizardite and chrysotile. Note the predominantly planar structure of the lizardite layers and the coiled or scrolled structure of the layers in the chrysotile. From Dódony, 1993.

Chrysotile is probably the least abundant serpentine mineral, but its typically fibrous habit makes it the most easily recognized (Wicks and O'Hanley, 1988). Asbestiform chrysotile has a structure in which the t-o layers are curved into cylinders or spirals (scrolls) (Figure 3). Fibrous chrysotile occurs in cross-fiber and slip-fiber veins, and sometimes as mass fiber deposits. Chrysotile is the most commonly occurring asbestos mineral in California. Chrysotile also occurs in a massive form (polygonal chrysotile) that cannot be distinguished from lizardite or antigorite without XRD or electron diffraction studies. This type of chrysotile occurs as a non-fibrous component of cross-fiber and slip-fiber veins, or as the sole component of veins or as coatings on shear surfaces in serpentinites (Wicks and O'Hanley, 1988).

Antigorite is intermediate in overall abundance between lizardite and chrysotile (Wicks and O'Hanley, 1988). The antigorite structure consists of t-o layers with a wave-like shape created by periodic inversions of the sheets (Figure 4). These inversions result in missing octahedra, which cause antigorite to be slightly higher in  $\text{SiO}_2$  content and lower in  $\text{MgO}$  and  $\text{H}_2\text{O}$  content than either lizardite or chrysotile. Antigorite can be massive, acicular, or pseudofibrous in habit.

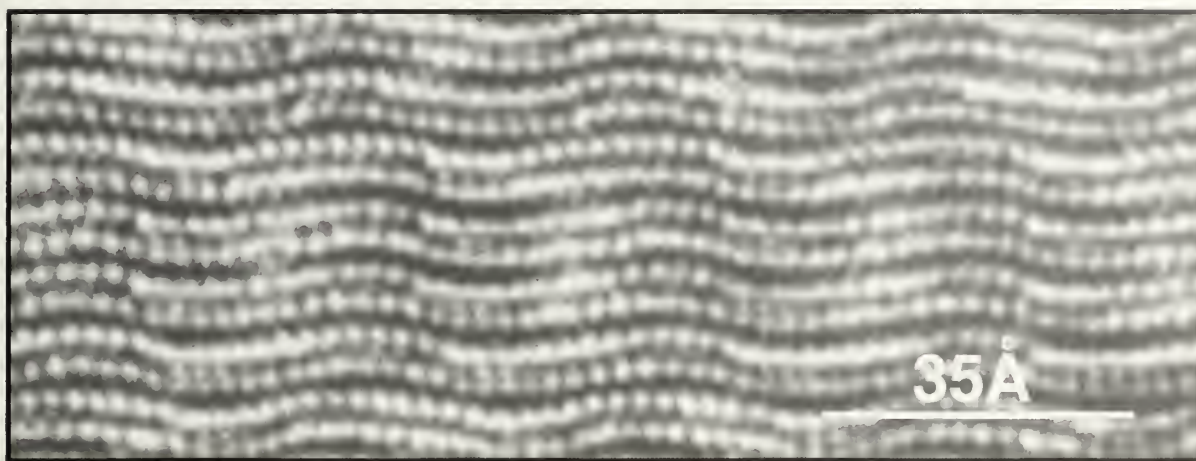


Figure 4: HRTEM image of antigorite showing the wave-like structure of the layers. From Dódoný, Pósfai, and Buseck, 2002.

## Discussion

One must be cautious in identifying serpentine minerals on the basis of habit. Chrysotile can form highly flexible asbestiform fibers that can be bent almost about their diameter. It can also form slickensides that produce splintery acicular fragments when broken. These fragments of chrysotile are similar to those expected from lizardite. The term “picrolite” describes a vein-filling serpentine that is typically apple green in color, and that may be either massive or pseudofibrous in habit. Because picrolite may be lizardite, chrysotile, antigorite, or a mixture of these minerals the term does not denote a particular mineral species but is a useful field term. When specimens of pseudofibrous picrolite are scratched with a knife, they form a powder, demonstrating that they are made up of pseudofibers, not actual mineral fibers.

Unless fibrous in habit, the serpentine minerals are seldom distinguishable from one another in either hand specimen or in thin section. Fibrous minerals occurring in serpentinite may be chrysotile or may be a non-serpentine mineral. Unequivocal identification of these minerals requires sophisticated X-ray diffraction (XRD) or transmission electron microscopy (TEM) techniques. With commercially available X-ray diffractograms, often the best interpretation one can make is to establish the presence or absence of a serpentine mineral, which could be either lizardite or chrysotile. XRD provides no information about the habit of chrysotile, asbestiform or polygonal (massive or pseudofibrous in habit) that is present in a sample. Wicks (2000) noted that many of the reference X-ray powder-diffraction patterns in common use over the last several decades for the serpentine minerals are inaccurate, misidentified, or of poor quality, making accurate identifications by this method difficult.

## The Amphibole Mineral Group

The amphibole group is very complex and contains numerous species due to the wide variation in possible chemical compositions. Many amphibole species can occur in the fibrous or asbestiform habit. This discussion will concentrate on the currently regulated amphibole species (Table 3). Note that the currently regulated asbestiform amphiboles all crystallize in non-asbestiform habits as well. General information on the properties of individual species that make up the amphibole group is available in Gaines and others (1997) and Anthony and others (1995). More detailed discussions of the amphibole group can be found in Deer and others (1997), Whittaker (1979), Hawthorne (1981), Hawthorne (1983), Zoltai (1981), and Veblen and Wylie (1993).

Table 3 – The Regulated Amphibole Asbestos Minerals

Regulatory Name	Mineral Name	Ideal Chemical Formula
Tremolite	Tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Actinolite	Actinolite	$\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Anthophyllite	Anthophyllite	$\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Crocidolite	Riebeckite	$\text{Na}_2(\text{Fe}^{2+}_3, \text{Fe}^{3+}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$
Amosite	Cummingtonite-Grunerite	$\text{Mg}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2 - \text{Fe}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$

The basic structural unit of the amphibole group is made up of two double chains of silica tetrahedra and a strip of octahedra. These are oriented such that the apices of the double chain tetrahedra point toward each other and sandwich the octahedral strip between them. The resulting unit is termed an “I-beam” because of its appearance in cross section (Figure 5). The length of the I-beam can extend indefinitely. Within the octahedral strip are three similar octahedral sites (labeled M1, M2, and M3) that may accommodate different size cations such as Fe, Mg, Al and Ti. These octahedral cations link the tetrahedral chains to form the “I-beams.” Between the I-beams is the larger, more irregular M4 site, which accommodates larger cations such as Na and Ca, as well as Fe and Mg. Cations in the M4 site cross-link the I-beams in the a and b crystallographic directions. Nestled in the center of the rings of tetrahedra formed by the double chain (Figure 5) are the O3 and A sites. In the cross-sectional view of the I-beam (Figure 5), the O3 site lies at the level of the apical oxygen of the tetrahedra and the A sites lie at the level of the basal oxygen of the tetrahedra. The O3 site is typically occupied by anions such as hydroxyl, fluorine, chlorine, or oxygen, and the A site by large cations such as Na or K.



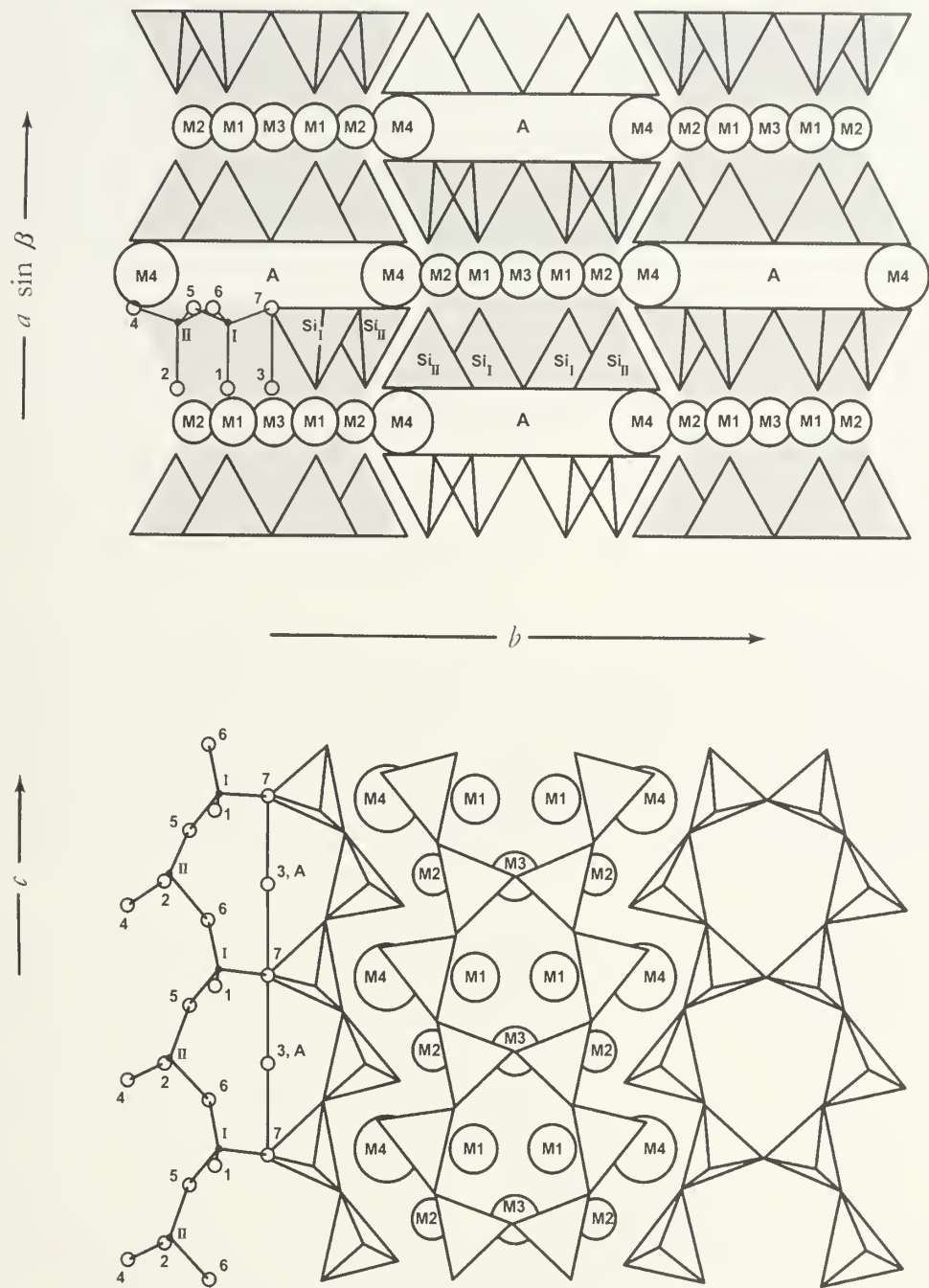


Figure 5. The above diagrams are representations of the amphibole crystal structure. The top diagram is an "end" view (looking along the c-crystallographic axis) and the bottom diagram is a "plan" view (looking along the a-crystallographic axis). The double-chains of silica tetrahedra, characteristic of amphiboles, is most easily seen in the lower figure and is represented by the patterns of upward oriented and downward oriented tetrahedra. The "I-beam" units discussed in the text are shaded in the upper figure. Sites M1-M4 are cation substitution sites. The A site is the structural location of large cations like Na and K. Anion positions are shown on the left-hand side of the diagrams by small open circles, 1-7; the O7 anion is generally hydroxyl or fluorine. Modified from Colville and others, 1966.

Amphiboles are classified according to the occupancies of the various sites in the structural formula unit of amphibole expressed as  $A_1B_2C_5T_8O_{22}(OH)_2$ . Here, A represents the occupancy of the A site, B the occupancy of the M4 site, C the occupancy of the M1, M2, and M3 sites, T the occupancy of the tetrahedral sites, and OH the occupancy of the O3 site in the six-membered rings. Amphiboles are classified as “calcic”, “sodic”, “sodic-calcic” or “iron-magnesium-manganese-lithium (Fe-Mg-Mn-Li)” amphiboles according to the dominant cations in the B position (Leake and others, 1997; Table 4). Some typical end-members, all of which are known to adopt an asbestiform habit, are listed below (note that the A position is vacant in all of these formulas as indicated by the “□” symbol).

Structural Unit Formula	$A_1B_2C_5T_8O_{22}(OH)_2$
Calcic: Tremolite	$\square Ca_2Mg_5Si_8O_{22}(OH)_2$
Sodic: Riebeckite	$\square Na_2(Fe^{2+}_3Fe^{3+}_2)Si_8O_{22}(OH)_2$
Sodic-Calcic: Winchite	$\square (CaNa)(Mg_4Al)Si_8O_{22}(OH)_2$
Fe-Mg-Mn-Li: Anthophyllite	$\square Mg_2Mg_5Si_8O_{22}(OH)_2$

Beyond the division into these sub-groups, amphiboles are further divided on the basis of the occupancy of other sites in the structural formula. Table 4 illustrates the classification criteria based on site occupancies for selected amphibole species. The complete classification system can be found in Leake and others (1997). For example, iron and magnesium may be freely substituted in these formula units and the formula for common actinolite differs from tremolite primarily by the substitution of 10% or more of the Mg by  $Fe^{2+}$ . Likewise, the formulas of monoclinic grunerite and orthorhombic anthophyllite differ primarily by the extensive substitution of  $Fe^{2+}$  for  $Mg^{2+}$ .

Several systems are available for naming amphibole minerals, all of which are based on composition. Any NOA report should include a reference to the system used in naming amphiboles in that report. One of the most current classifications is that proposed by the International Mineralogical Association (Leake and others, 1997). Precise identification of amphibole minerals requires detailed compositional information, which is commonly not available. If only the approximate nature of the amphibole is known, for example using only optical properties, Leake and others (1997) recommend that the nearest amphibole name should be used as an adjective followed by the word amphibole (e.g., *anthophyllitic* amphibole or *tremolitic* amphibole). Leake and others (1997) recommend that asbestiform amphiboles be named according to their precise mineral name followed by the suffix-asbestos (e.g., anthophyllite-asbestos, tremolite-asbestos). If only the approximate nature of the amphibole asbestos is known, the nearest amphibole name should be used as an adjective followed by the word asbestos (e.g., anthophyllitic asbestos, tremolitic asbestos). If the nature of the mineral or amphibole is uncertain, asbestos alone or amphibole-asbestos may be used. The naming conventions proposed by the International Mineralogical Association (Leake and others, 1997) have been used throughout these Guidelines.

Table 4 – International Mineralogical Association 1997 Classification Criteria for Selected Amphibole Minerals ( $A_1B_2C_5T_8O_{22}(OH)_2$ )

Mineral Name Ideal Formula <sup>1</sup>	Amphibole Sub-Group (Crystal system)	Ca (A site)	Na + K (A site)	Ca (B site)	Ca + Na (B site)	Na (B site)	Mg/Mg+Fe <sup>2+</sup>	Si atoms (max of 8,0)
Tremolite □ Ca <sub>2</sub> MgSi <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Calcic (monoclinic)	<0.50	<0.50	≥1.50			0.9-1.0	7.5-8.0
Actinolite □ Ca <sub>2</sub> (Mg,Fe <sup>2+</sup> ) <sub>3</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Calcic (monoclinic)	<0.50	<0.50	≥1.50			0.5-0.9	7.5-8.0
Richterite Na(Ca,Na)Mg <sub>5</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Sodic-Calcic (monoclinic)		≥0.50		≥1.00	0.50-1.50	0.5-1.0	7.5-8.0
Winchite □ (Ca,Na)(Mg,Al)Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Sodic-Calcic (monoclinic)		<0.50		≥1.00	0.50-1.50	0.5-1.0	7.5-8.0
Riebeckite <sup>2</sup> □ Na <sub>3</sub> (Fe <sup>2+</sup> <sub>3</sub> ,Fe <sup>3+</sup> )Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Sodic (monoclinic)		<0.50			>1.50	0.0-0.5	7.5-8.0
Anthophyllite <sup>3</sup> □ Mg <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Mg-Fe-Mn-Li (orthorhombic)				<1.00		0.5-1.0	7.0-8.0
Cummingtonite <sup>3</sup> □ Mg <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Mg-Fe-Mn-Li (monoclinic)				<1.00		0.5-1.0	7.0-8.0
Grunerite <sup>3</sup> □ Fe <sup>2+</sup> <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	Mg-Fe-Mn-Li (monoclinic)				<1.00		0.0-0.5	7.0-8.0

<sup>1</sup>□ indicates a vacant A site  
<sup>2</sup>riebeckite additional criteria: (Mg + Fe<sup>2+</sup> + Mn<sup>2+</sup>)>2.5; (<sup>VI</sup>Al or Fe<sup>3+</sup>)>Mn<sup>3+</sup>; Li<0.5; (Mg or Fe<sup>2+</sup>)>Mn<sup>2+</sup>  
<sup>3</sup>anthophyllite, cummingtonite and grunerite additional criteria: (Mg, Fe<sup>2+</sup>, Mn, Li) in B site=1.00; Li in B site<1.00

### **Other Asbestiform Minerals**

The six commercial asbestos minerals are the best known naturally occurring asbestiform minerals, but many other minerals such as brucite, erionite, talc, tourmaline, palygorskite, sepiolite, and others can crystallize in the fibrous habit under the right conditions (Zoltai, 1981; Skinner and others, 1988). When asbestiform, some of these other minerals may have the physical properties of asbestos (high tensile strength, flexibility, etc.). However, none of these other potentially asbestiform minerals have been found in quantities large enough for economic exploitation as asbestos and therefore would not be considered asbestos by the commercial definition. Nor are any of these other asbestiform minerals currently part of the regulatory definition of asbestos in California. Some of these potentially asbestiform minerals may occur in the same, or similar, geologic settings as the more common asbestos minerals. For example, carlosturanite occurs in some serpentinites and may be associated with chrysotile (Compagnoni and others, 1985; Mellini and Zussman, 1986; Wicks and O'Hanley, 1988), and many amphibole minerals, including richterite and winchite, and arfvedsonite, may occur in asbestiform habits in a variety of geologic settings. Some of these potentially asbestiform minerals such as erionite and winchite-asbestos are known to, or suspected of, posing a health risk similar to that of the regulated asbestos minerals (Wylie and Verkouteren, 2000; Ross and others, 1993). The fact that minerals other than the six commercial asbestos minerals can occur in the asbestiform habit means that a geologist in the field should not assume that an asbestiform mineral is either a serpentine or an amphibole based on appearance or physical properties alone. Confirmatory laboratory analysis will often be needed to positively identify asbestiform mineral samples (see section on Analytical Methods). Synthetic fibers, termed whiskers, can also possess the properties of asbestiform fibers. Whiskers have been made from Carbon, ZnS, NaCl,  $\text{Al}_2\text{O}_3$ , ZnO, MgO,  $\text{SiO}_2$ , and  $\text{Mg}_2\text{SiO}_4$ , and other chemicals (Zoltai, 1981; Skinner and others, 1988), indicating that many materials will crystallize with the asbestiform habit under appropriate conditions.



THE GEOLOGIC OCCURRENCE OF THE ASBESTOS MINERALS

Introduction

This section reviews the geologic occurrence of the asbestos minerals. While economic deposits of the asbestos minerals are rare, small non-economic occurrences of asbestos mineralization, which may be of environmental concern, are more common. Commercial deposits of asbestos have been associated with the following rock types; alpine-type ultramafic rocks including ophiolites and serpentinites, stratiform ultramafic intrusions, serpentinitized carbonate rocks, and banded iron formations (Ross and Virta, 2001; Ross, 1981). In California, asbestos mineralization is most commonly found in and immediately adjacent to ultramafic rock bodies, but is known to be present in other geologic settings as well (Churchill and Hill, 2000). Table 5 summarizes information on the geologic settings of asbestos deposits in California drawn from various publications of the Division of Mines and Geology (now known as the California Geological Survey). Most of these publications reported on economic or potentially economic asbestos occurrences and this list should not be considered a complete listing of the possible geologic settings in which asbestos may occur in the state. However, the list does illustrate some of the variability in asbestos occurrence in California.

Table 5. Summary of Geologic Settings for Asbestos Occurrences in California, from Reports of the State Mineralogist (1887-1955), County Reports, and Bulletin 189.

Geologic Setting (as reported)	Asbestos Type
Serpentinite (or serpentinitized peridotite)	Chrysotile, Tremolite, Anthophyllite
Altered gabbroic inclusions in quartz diorite (asbestos associated with vermiculite in these inclusions)*	Chrysotile
In silicified serpentinite*	Amphibole asbestos
A “granular olivine-hornblende rock”*	Amphibole asbestos
A “shear zone in granite”*	Amphibole asbestos
Piemontite schist*	Tremolite
Limestone, “crystalline” limestone or marble (contact metamorphic area)	Tremolite
In dolomitic limestone along a belt of serpentinite	Chrysotile and amphibole asbestos
Dolomite	Chrysotile
Nickel laterite	Chrysotile
Shale*	Asbestos
Serpentinite/amphibolite contact	Amphibole asbestos
Serpentinite/slate contact	Tremolite
Slate/granite contact*	Anthophyllite
In schist and serpentinite*	Amphibole asbestos
In boulders with nephrite and jadeite*	Riebeckite asbestos (crocidolite)
Albitite*	Riebeckite asbestos (crocidolite) or acicular riebeckite
Schists*	Anthophyllite asbestos

\* Only one such occurrence was reported in the literature reviewed.

Ultramafic rocks are igneous rocks such as peridotite, dunite, pyroxenite, and hornblendite that contain greater than 90% of olivine, pyroxene or hornblende (International Union of Geological Sciences, 1973; Le Maitre, 1989; Le Bas and Streckeisen, 1991). "Ultramafic" is also a chemical term that is applied to peridotite, dunite, pyroxenite, and serpentinite. Most ultramafic rock bodies in California are variably altered to serpentine but should only be called serpentinite if they contain more than 50% serpentine minerals (Coleman, 1971). Ultramafic rocks containing less than 50% serpentine minerals should be referred to as serpentinitized ultramafic rocks.

The physical conditions leading to the crystallization of the asbestos minerals are not well understood. Any rock that ordinarily has the correct chemical composition to contain amphibole or serpentine minerals may host amphibole-asbestos or serpentine asbestos. However, the non-asbestiform habits of these minerals are much more common than the asbestiform habits. In addition to favorable chemical composition, asbestos deposits are also more likely to occur in areas subjected to differential stress and enhanced fluid access. Consequently, both types of asbestos are more likely to be found in areas where permeability and fluid flow have been enhanced, such as in fault or shear zones and contact metamorphic aureoles.

### **Serpentine Asbestos**

Serpentine asbestos occurs most commonly in serpentinites and partially serpentinitized ultramafic rocks. Serpentine asbestos is nearly always chrysotile, but also may be carlosturanite (Wicks and O'Hanley, 1988, p. 123; Compagnoni and others, 1985; Mellini and Zussman, 1986). Chrysotile is the most commonly occurring asbestos mineral in California. In serpentinites and ultramafic rocks, serpentine minerals typically form at relatively low temperatures (below 500 °C) as hydrous alteration products of olivine and pyroxene. Serpentine minerals may also form by recrystallization at low temperatures (150 - 350 °C) from previously altered and serpentinitized rocks. More detailed discussion of the paragenesis of the serpentine minerals can be found in Wicks and O'Hanley (1988) and O'Hanley (1996).

Bodies of serpentinite are commonly strongly tectonized and associated with faults or shear zones. In these serpentinite bodies chrysotile typically occurs as parallel fibers at high angles to the walls of well-defined veins (cross-fiber), or as fibers parallel to the margins of the vein or surface on which they are found (slip-fiber). During deformation, both slip surfaces and fractures at high angles to the least compressive stress direction may develop that allow access of fluids that promote the formation of fibers. Consequently, it is not unusual to find both cross-fiber and slip-fiber veins in the same outcrop. Cross-fiber asbestos veins in serpentinite are typically, but not exclusively, composed of chrysotile; therefore the mineralogy of such veins should be confirmed by laboratory analysis. In pervasively sheared or cataclastic rocks, chrysotile may also occur as mass fiber deposits. Mass fiber asbestos consists of randomly orientated fibers and may have an appearance quite different from cross-fiber or slip-fiber asbestos. Mass fiber asbestos has sometimes been referred to as "Mountain Leather" or "Mountain Cork" because of its appearance. The New Idria area of California contains large deposits of mass fiber chrysotile in which the fibers are unusually short (a few microns or less) and occur in soft friable aggregates and also in leathery sheets (Mumpton and Thompson, 1975). In some serpentinitized dunite, chrysotile asbestos occurs as a pervasive component of the rock, representing up to 90% of the mineral mode. The fibrous or asbestiform habit of chrysotile in this type of deposit may not be obvious in hand sample. Weathering and erosion of asbestos-containing outcrops of ultramafic rock sometimes form small irregular felted masses of asbestos fibers that may be distributed over the face of the outcrop or at the base of the exposure.

Chrysotile occurs less commonly in other rocks that contained original olivine or pyroxene such as hydrothermally altered or metamorphosed mafic intrusive igneous rocks (such as gabbro) or mafic volcanic rocks that are commonly associated with ultramafic rocks and serpentinite.

Chrysotile may also occur in metamorphosed carbonate rocks such as magnesian marbles or meta-dolostones where serpentine minerals may form by retrograde alteration of metamorphic olivine or possibly by direct contact metamorphism of siliceous dolostones.

### **Amphibole Asbestos**

Amphibole asbestos is less common than chrysotile asbestos in California. Tremolite-asbestos and actinolite-asbestos are probably the most common types of amphibole-asbestos in California, but anthophyllite-asbestos, riebeckite-asbestos (crocidolite), and cummingtonite-grunerite-asbestos (amosite) may also occur. Amphibole asbestos is most commonly found in metamorphosed equivalents of ultramafic rocks including serpentinite, mafic plutonic rocks, mafic volcanic rocks, Fe-cherts, and ironstones. Amphibole asbestos is also known to occur in metamorphosed carbonate rocks and, less commonly, in metamorphosed granitic rocks. In any of these metamorphosed rocks, non-asbestiform amphibole may be common, and subsequent deformation or hydrothermal activity may lead to the crystallization of amphibole-asbestos. Like serpentine asbestos, amphibole asbestos and other fibrous amphiboles may occur in both slip-fiber and cross-fiber veins and as mass fiber deposits. More detailed discussion of the paragenesis of the various amphibole minerals can be found in Deer and others (1997) and in Robinson and others (1982).

Calcic amphibole, typically tremolite or actinolite, is commonly found in altered ultramafic rock or serpentinite bodies (due to local silica and calcium enrichment) in proximity to wall rocks, tectonic inclusions, dikes (including rodingites), and former fluid pathways provided by faulting and shearing. These minerals also occur in metamorphosed or altered mafic plutonic or volcanic rocks that are commonly associated with ultramafic rocks and serpentinite, in talc-rich rocks (steatite), in medium-grade metadolomites, and in pseudomorphic aggregates (uralite) replacing ferromagnesian minerals in altered igneous rocks. Under appropriate conditions, tremolite-asbestos or actinolite-asbestos may also occur in these settings but is less common than the non-asbestiform varieties.

Sodic amphiboles, such as riebeckite, may be found in relatively sodic alkalic igneous rocks such as granites and syenites, in carbonatites and associated rocks, and in association with medium- to high-grade schists and metamorphosed Fe-rich chert and ironstone. The most common occurrence of riebeckite-asbestos (crocidolite) is in metamorphosed ironstone or Fe-chert. The occurrence of riebeckite-asbestos (crocidolite) in igneous rocks is not common but may result from metamorphism or metasomatism of the original rock. Similarly, metamorphosed or metasomatized carbonate rocks may host riebeckite-asbestos (crocidolite).

The Mg-Fe-Mn-Li amphibole anthophyllite is characteristic of ultramafic rock that has undergone medium grade regional or contact metamorphism. Anthophyllite commonly occurs in association with tremolite, cummingtonite, and talc in this setting and can be abundant both as a pervasive component of the rock or in veins. Fibrous or asbestiform anthophyllite may occur as radiating fibrous aggregates or as veins.



The Mg-Fe-Mn-Li amphiboles cummingtonite and grunerite occur in both igneous and metamorphic rocks but occur most commonly in medium grade regionally and contact metamorphosed rocks. Cummingtonite-grunerite-asbestos (amosite) most commonly occurs in metamorphosed ironstone or Fe-chert.

### **Asbestos in Sedimentary Rocks**

Asbestos-containing rocks may be eroded and transported to form sedimentary and alluvial deposits. Sedimentary serpentinite and serpentine as a component of other sedimentary rocks occur in California, where exposure, erosion, and redeposition of both serpentinite and asbestiform serpentine have been ongoing since Jurassic time. The Miocene Big Blue Formation is a sedimentary serpentinite in the California Coast Ranges (Casey and Dickinson, 1976) and when subject to erosion is a source of alluvial asbestos. Recent mass wasting of serpentinite in the Coast Ranges was described by Cowan and Mansfield (1970). Alluvial deposits containing asbestiform materials are likely to be found in any watershed that drains ultramafic rocks. In fact, waters in many California streams from watersheds containing ultramafic rocks contain asbestos fibers (Hayward, 1984).

### **Asbestos in Soils**

Soils derived from parent materials containing chrysotile and amphibole asbestos also contain asbestos fibers and are an important potential source of airborne asbestos. The formation of soils on ultramafic rocks is discussed in Alexander and others (1985), Brooks (1987), Schreier (1989), and Trescases (1997). Weathering and leaching reduce the amounts of asbestos in soils over time. We know very little about the rates of weathering and leaching of asbestos in soil environments, but the available information suggests that substantial reductions in the amount of chrysotile may take hundreds or thousands of years, depending on the soil environment, and somewhat longer for amphibole asbestos. Acid leaching removes magnesium from chrysotile fibers relatively rapidly, leading to their disintegration. Amphibole asbestos is typically more resistant to attack by acids. However, most serpentine soils in California are initially slightly alkaline to neutral and become more acid as they age. Only very old, leached California serpentine soils, on the order of 10,000 to 100,000 years old, are moderately to strongly acid.

Shallow, gray serpentine soils are more likely to have high concentrations of asbestos fibers than are deep, red serpentine soils. Reddish hues are imparted to soils by the release of iron from primary minerals and its oxidation to form iron oxides. The red colors indicate that the processes of weathering and soil formation have been particularly intense or have been active for a long time. Asbestos fibers, at least chrysotile fibers, would be expected to be less abundant in moderately acid soils with reddish hues. Asbestos fibers found in soils may be smaller than those found in the parent materials due to chemical and physical weathering. The presence of asbestos fibers in soils may be of interest if the soils are proposed as a capping material for NOA exposures. The presence of asbestos fibers may also be a concern if the soils are to be moved off site for disposal. Soil or rock containing friable asbestos may meet hazardous waste criteria and require special handling.



## **SITE INVESTIGATION**

### **Preparation**

As with any geologic field study, a preliminary office review of the available information will assist the geologist in designing an efficient investigation and sampling and analysis program for NOA. Many of the common sources of information used in geologic studies (geologic maps, reports, aerial photos, water well logs, etc.) may be useful in NOA studies. However, there are some aspects of NOA studies that deserve special consideration at this phase of the geologic study such as the intent and purpose of the proposed project, prior site use, inconsistent use of rock names in prior reports, and the utility of soils maps.

### **Scope of Work and Field Investigative Methods**

It is important to consider the intent and purpose of the proposed project in developing a geologic investigation for NOA. The type of project will influence the physical extent, both areal and vertical, of the investigation as well as the investigative methods used. For example, to evaluate the NOA potential to the limits of the deepest excavation for a proposed single family dwelling may require investigation to depths of a few feet to a few tens of feet. In contrast, an evaluation for a large project, which will involve large and/or deep excavations, may require more extensive exploration and sampling to assess the potential occurrence of NOA to the limits of any proposed excavation. The geologist will have to select the appropriate investigative methods based on the proposed design, site conditions, site geology, and applicable regulatory requirements. It may be necessary to extend the investigation beyond the boundary of the principal site or property to adequately evaluate the potential presence of NOA at the site. Areas of the site with pre-existing roads or fill areas should be identified and the material used in their construction should be examined. It is also important to determine if such material originated on-site or if it was imported. Asbestos-containing materials and products have historically been used in construction and manufacturing in the United States. The potential for site contamination due to prior use of asbestos-containing materials or products should be evaluated for sites with prior development.

A site visit by the geologist is essential to verify geologic conditions suggested by office and library research. Depending on the detail and intent of previous geologic studies, geologic features that could host asbestos may not have been identified or documented. In addition, in many areas there is a possibility of asbestos-containing rock or earth material being present on the site as imported fill or landscape rock even though the native site materials do not contain asbestos.

### **Review of Geologic References**

In reviewing geologic references and maps prior to conducting field investigations for NOA, it is important to consider the original intent of the reference or map being reviewed. Unless the report or map was specifically prepared to evaluate the occurrence of NOA, the presence of asbestos minerals may not be mentioned because their presence was not important to the particular study.

The geologist should be aware that the terms “ultramafic rock” and “serpentinite” (or ultrabasic rock or serpentine in the older literature) have often been used inconsistently in geologic reports and maps. Because of the continuous gradation in the degree of metamorphism in ultramafic rocks, the use of the terms “serpentinite” and “ultramafic rock” in the geologic literature is arbitrary. Some geologists have suggested that this boundary should be at 50% serpentine minerals (Coleman, 1971). However, this suggestion has not been universally adopted or applied by geologists working in areas containing ultramafic rocks in the past. In many geologic studies, the differentiation of serpentinite from ultramafic rock is not important to the goal of the study and the distinction is not made. Rather, a single unit called “ultramafic rock” or “serpentinite” has commonly been used in geologic mapping and reports. This unit may include any combination of serpentinite and ultramafic rock.

Review of geologic and NOA reports on file at local or State agencies, insofar as they apply to the property under consideration, can be an important part of a NOA investigation. Relevant reports should be cited and their conclusions relating to adjacent and nearby properties summarized.

### **Use of Soil Maps**

Asbestos minerals may be found not only in bedrock but also in soil or sediments derived from asbestos-containing bedrock. In such cases, soil maps may assist the geologist in evaluating the likelihood of asbestos occurrence as well as the extent and distribution of potentially asbestos-containing materials on the site. Contacts for soils information are included in Appendix C. Soil maps and reports for the project site should be reviewed to determine if any of the mapped soil units are specifically derived from, or overlie, potentially asbestos-containing geologic formations. This is often useful in ultramafic terrains where soils derived from ultramafic rocks or serpentinite will be identifiable as “serpentine soils” or “ultramafic soils” on soil maps.

Some soil maps may contain areas labeled “serpentine rock area.” There may be several different soil types related to serpentinite/ultramafic rock, with different names and different areas of occurrence, on a given soil map. The description of each soil unit (provided in the report accompanying the soil map) should be reviewed to ensure that all areas of serpentinite/ultramafic rock related soils are identified. In many cases, review of both geologic and soil maps for the project site and surrounding area will provide the geologist with a more complete picture of the possible extent and distribution of NOA at the site. If no soil maps are available and the information is critical to the project, a Certified Professional Soil Classifier (American Registry of Certified Professionals in Agronomy, Crops, and Soils) should be consulted for soil classification.

### **Vegetation**

In areas containing ultramafic rocks and serpentinite, the high-Mg chemistry of these rocks and the soils derived from these rocks often host distinctive or unique plant communities. Information on the geographic occurrence of some rare plant species may be available from federal, state or local agencies. If the species is specific to ultramafic or serpentine soils, this information may be useful in mapping the distribution of these soils. Additionally, vegetation density and size may be useful indicators as vegetation in these areas is often sparse and stunted due to the poor soil development and soil chemistry. The vegetation associated with ultramafic and serpentinitic rocks and soils is discussed in Brooks (1987) and Kruckeberg (1984) and examples may be illustrated at the California

Native Plant Society web site ([www.cnps.org](http://www.cnps.org)). These plant communities may vary in composition due to other influences, so a serpentine soil in the foothills belt of the Sierra Nevada may have a different plant assemblage than a serpentine soil in the Coast Ranges or even in another part of the foothills belt. However, the presence of distinctive vegetation may assist in mapping the distribution and areal extent of these units both in the field and on aerial photographs or other types of remote sensing imagery.

### **Miscellaneous Sources of Information**

Aerial photographs may provide information about site geology and geologic structures such as shear zones that may host asbestos mineralization. Aerial photographs may also reveal information about the recent and historic uses of a site and the surrounding region. Current and out-of-print U.S. Geological Survey topographic maps should be reviewed for relevant information. In some urban areas Sanborn Fire Insurance Maps or old city directories may provide information about past site use.

### **Geologic Mapping**

The primary purpose of geologic mapping in a NOA investigation is to identify asbestos-bearing or potentially asbestos-bearing rock or soil units and to describe their occurrence and distribution on the project site. Emphasis should be placed on identifying and describing those geologic units or features that may host or influence the distribution or transport of NOA at the site. The potential for disturbance of asbestos-bearing units in the mapped tract to impact nearby surface water should also be noted. Site areas containing fill or other imported earth material should be examined to determine if the materials contain asbestos.

### **General Considerations**

Geologic mapping should be compiled on a suitable base map. Generally, a topographic base map, if available, is preferred as an aid to accurate depiction and interpretation of the site geology unless more detailed, higher resolution, project development maps exist. The map scale is controlled by the size of the investigated area. A topographic or planimetric base map of the selected areas should be tied to the local land survey system (county or city). The location of any permanent land survey markers should be plotted on the base map. Drainage, man-made features, scattered elevations or topography, and distribution of vegetation should be added to the base map when they are available. If U.S. Geological Survey quadrangle maps or orthophotos are available they may contain much of this information. The boundaries of any proposed excavation or grading should be shown. Geologic mapping of the site should be planned, conducted, and documented in accordance with standard procedures such as those found in U.S. Bureau of Reclamation (1998).

Sample locations should be shown on the map and the coordinates (latitude-longitude or Universal Transverse Mercator coordinates and the map datum used) of the sample locations included in the report. If sample locations are referenced to a site grid, the grid should be referenced to identifiable features so that sample locations can be relocated, if necessary. The type of sample (targeted or unbiased) should be indicated. If air monitoring is being conducted, the locations of the air monitoring stations should also be included. Locate any previous asbestos sampling or air monitoring sites on the map.



If appropriate, geologic cross sections may be constructed at the same scale, or at higher resolution, as the geologic map and extended to reasonable depths (at least the depth of any proposed excavation). The purpose of geologic cross sections in a NOA investigation is to show the geologic rationale for predicting the occurrence or absence of NOA in areas to be excavated during construction activities. Small sites may not yield enough structural data to construct a cross section.

## **Mapping**

Contacts between different geologic units should be shown on the geologic map and the nature of the contacts should be described. The orientation of structural features such as folds, faults, joints, and rock fabric (e.g., lineations, schistosity, bedding) should be recorded and their relationship to asbestos mineralization noted. The degree of weathering should be noted and any relationship between weathered zones and asbestos mineralization described. The locations and orientations of asbestos bearing veins should be plotted on the map and their type (cross-fiber or slip-fiber), width, extent, and relationship to structural features described. The thickness, color, texture, and friability of asbestos veins should be described.

In certain situations, it may be preferable to map zones containing numerous, small asbestos veins or occurrences rather than individual veins. For veins of slip-fiber asbestos in serpentinite, determine the distribution pattern in the sheared serpentinite as related to faulting. Highly sheared serpentinite may contain up to 40-50% slip-fiber asbestos. Estimates of the volume percent of asbestos bearing veins in the outcrop should be made if possible.

Asbestos occurrences in non-ultramafic rocks such as limestone-dolomite or gabbro should be carefully described. The asbestos in these rocks forms under different geologic conditions than the asbestos in ultramafic rocks, which may give rise to different or distinct NOA distribution patterns in these settings.

Erosion of asbestos-bearing ultramafic rock may be substantial, forming extensive sedimentary layers in marine and non-marine deposits. Sedimentary serpentinites or sedimentary rocks containing detrital serpentinite or ultramafic rock should be plotted and described. Recent alluvial deposits derived from asbestos-containing parent materials should be mapped and described.

## **Lithology**

The lithology of bedrock units should be identified in the field if possible and confirmed in the laboratory by petrographic methods if necessary. Hand-specimen descriptions of rock-types found in the study area (done with the aid of a hand lens) should attempt to detail insofar as possible the following: rock name, mineralogy, heterogeneity (at sample, outcrop and map-scale), metamorphic grade, structures, and presence of veins or alteration. When necessary, examination of thin sections by an experienced petrographer places rock-type identification on a firmer footing and can provide information on mineral associations, textures, type and amount of alteration, and metamorphic grade. An evaluation of the prevailing metamorphic type (regional or contact) and grade (low, medium, or high) can be important because some of the asbestos minerals are restricted in occurrence to rocks of certain metamorphic grades (e.g., anthophyllite which occurs in rocks of medium grade). It is important to realize that asbestos minerals may be pervasively present in small amounts in some



occurrences (and not necessarily visible in hand samples), as well as occurring in obvious veins in others. In most instances, field identifications of potential asbestos minerals will need to be confirmed by microscopic or more sophisticated methods.

Serpentinite and partially serpentinized ultramafic rock are the most common host rocks for asbestos in California. These rocks typically show irregular variations in the degree of serpentinization. The least serpentinized ultramafic rocks are blocky and dark reddish-brown gradually changing to shiny, green-black sheared material as the degree of serpentinization increases. The map should portray the areal extent of these features and their relationship to faulting or other structural features. Other lithologic features related to the heterogeneity of the ultramafic rock should be noted such as brecciation or metamorphic fabrics. Landslide deposits, including mudslides, earth flows, etc., derived from ultramafic rock can also contain asbestos bearing material. The boundaries of the landslide and direction of its movement should be noted and the presence or absence of asbestos investigated.

### **Soils**

Soil contacts are typically gradational. On hilly surfaces, the probable erosional or soil creep directions of the soil should be indicated. Distinguishing between alluvial, colluvial and residual soils in a NOA study can be important. Different soils may have different parent materials and therefore, different potentials for containing asbestos. Soils may be identified by name from USDA soil maps or other sources if available.

Residual soils developed on ultramafic bedrock should be investigated for asbestos. Individual asbestos fibers, or small bundles of fibers, are typically not detectable in hand samples of soils in the field and laboratory analysis will usually be necessary. Asbestos fibers may be assumed to be present in soils containing rock fragments with chrysotile or amphibole asbestos. The detection and identification of asbestos fibers in soil is difficult and should be carried out by a qualified laboratory.

## SAMPLING FOR NATURALLY OCCURRING ASBESTOS

### Introduction

A geologist may be called upon to assess the potential for NOA at sites with widely varying degrees of development, disturbance, and prior geologic observation. Generally, these Guidelines address the typical cases of:

- 1) Evaluating NOA potential on an existing residential, commercial, or industrial site, whether developed or undeveloped, in support of a purchasing decision or for real estate disclosure purposes, or
- 2) Planned construction of an engineered structure requiring a grading and (or) building permit.

In the first case, sampling may be limited to surface or near surface, except where natural erosion or previous excavations locally allow access to the subsurface. In the second case, subsurface information and samples relevant to NOA determination will generally be obtained as part of the normal sequence of geologic and geotechnical investigations and observations that support site development and construction. A program designed specifically to produce subsurface samples for NOA determination may not be economically or scientifically justifiable for many small sites or developments. In such cases, opportunities for subsurface sampling should be exploited during subsurface exploration carried out for other project purposes. All conclusions from an initial or subsequent assessment of NOA potential on a site should be verified and confirmed or changed by taking advantage of later opportunities to observe and sample as the site goes under construction, unless the initial observations can positively preclude the presence of NOA during site development.

Only general guidance regarding sampling methods is provided in these guidelines. The goals and needs of the project will influence the type and number of samples, the sample collection method, and the type of analysis required. Some projects may only require qualitative information while others will require quantitative analyses. Some projects may require only information on the surficial occurrence of NOA while other projects may require exploration and characterization of NOA at depths. The geologist should consider the impact of the sampling method on the validity of the sample and apply methods most likely to yield valid and representative samples. General information about sample management, protocol, and quality assurance and quality control have been summarized by the U.S. Bureau of Reclamation (1998) and suggestions for field sampling can be found in U.S. Bureau of Reclamation (1990, see especially Designations 7000, 7010, 7100, and 7105).

### Number of Samples and Data Reporting for NOA Studies

When sampling for NOA, the goal may be qualitative or quantitative characterization. If the goal is to determine the presence of asbestos at the site then a single sample found to contain asbestos may be sufficient. Although one sample may be sufficient to confirm the presence of asbestos, it is not possible to confirm its absence unless an entire site is excavated and analyzed. This is, of course, an unrealistic endeavor. In any field investigation, the number of samples collected should be sufficient to represent the site. If none of the samples contains asbestos, the conclusion should be that asbestos was not found and that the samples are thought to be representative of the site.

If the goal of field sampling is a quantitative assessment of the amount of asbestos present, the number of samples necessary to estimate the amount of asbestos with acceptable precision is an important concern. Determining the necessary number of samples requires knowledge of the statistical variance of the entire population under study and that the population be normally distributed. In a geologic study, and NOA sampling in particular, neither of these is known and the necessary number of samples cannot be precisely specified. Griffiths (1967) offers the following guidelines for sampling design:

- 1) The more specimens that are collected in the field, the greater is the precision;
- 2) When increasing precision in this manner, a balance should be achieved between the cost of additional sampling (and analysis) and acceptable precision.

Griffiths (1967) states further:

“...the literature on sampling applied to geological populations is steadily growing, but until specific experiments aimed primarily at solutions to geological sampling problems are completed, no very exact guide of general use can be expected.”

In the three decades since this was written, the literature is still limited on this matter and this remains a relevant statement today.

The situation with sampling just described has important consequences for the reporting of NOA analytical data. Because no exact guidelines exist for determining the number of specimens that should be collected, any statistics that are computed using quantitative results from analysis of these specimens cannot be interpreted to be “representative” of the entire NOA population. For example, suppose the analytical results for three samples are 0%, 5% and 10% asbestos. The mean, or average, of these three values is 5%, but the variability is considerable. Simply reporting the average value, 5%, says nothing about this variability. It is not correct to say that the average NOA concentration for the entire site is 5% because it is not known, nor can it be known, that the three specimens are representative of the entire population. More information is conveyed in a report by listing the three values, thereby showing the variability, then summarizing them with a statement to the effect that the asbestos content in select specimens ranged in value from 0% to 10%, thus indicating a presence of NOA on site.

Because these are guidelines for geologic investigation of NOA, and necessarily general, no further recommendations are presented regarding analysis of sample data. Further analysis may include the calculation of statistics such as mean quantity or comparative analysis such as statistical hypothesis testing comparing sample data to some criteria for NOA. Discussion of the various methods of data analysis is beyond the scope of these Guidelines and the reader should consult a geostatistics reference for more information (for example, Carr, 2002; Davis, 1986; or Isaaks and Srivastava, 1989).

### **NOA Sampling Strategy**

Geologic sampling for NOA falls into two basic categories, “targeted” and “unbiased.” Sampling based on geologic inference is called targeted, or directed sampling. A statistician calls this type of sampling biased. The purpose of targeted sampling is to verify qualitative observation and human



inference. Unbiased sampling refers to sampling conducted on a non-geological (non-targeted) basis. Unbiased sampling is also referred to by some as “random” sampling, but the latter term is avoided here because of its inherent statistical implications. Statistical “randomness” cannot be demonstrated if the statistical characteristics of the population are not known.

An additional sampling approach that may have application to NOA investigations, under special circumstances, uses univariate spatial analysis techniques (variograms and kriging). These techniques were developed in the 1960s by the mining industry for ore reserve estimation. They may be applied to address such issues as what is the optimum sample spacing or drill hole spacing required to determine the asbestos content of an exposed area or volume of rock. However, this approach is sample intensive and requires preliminary test sampling of one or more portions of the site in order to determine the sample spacing needed to evaluate the entire site. Consequently, this approach is likely to be expensive, time consuming, and applicable only in those cases where the asbestos content of a volume of in-place rock or soil at a site must be known with a high degree of accuracy. In such cases, a geostatistician knowledgeable about this technique should be consulted. Detailed discussion of these techniques is beyond the scope of these Guidelines, but numerous publications and professional journal articles exist for those wishing to investigate this approach further (for example, see Carr, 2002, pp. 85-131; Davis, 1986; or Isaaks and Srivastava, 1989).

### **Targeted Sampling**

A targeted sample is obtained to confirm the presence or absence of asbestos in a geologically representative sample from a particular location, geologic feature or unit. Targeted samples are relatively easy and inexpensive to collect and are typically used for site and feature screening purposes. In using this approach, it must be remembered that the character and appearance of NOA can vary substantially from one location to another within a site. Laboratory analysis of targeted samples provides data needed to confirm field observations of asbestos presence or absence and asbestos type. Potential sources of targeted surface samples for a NOA study include:

- Veins of fibrous or acicular (needle-like) appearing minerals in rock outcrops and float
- Zones of contact metamorphism in ultramafic rocks, serpentinite and carbonate rocks
- Sediment or soil in local topographic depressions
- “Geologically representative” appearing rock or soil for a particular area of a property
- Zones of cataclastic rocks, which are indicative of deformation
- Fibrous or acicular mineral occurrences in fault zones

In addition to materials that are native to the site, some sites may contain imported materials such as fill and landscape rock that should also be considered for sampling.

Targeted sampling could also encompass the taking of geologically representative samples of rock from an outcrop for rock-type identification by petrographic methods. Such rock-type identification may be necessary for determining the applicability of the CARB asbestos ATCM rules for a particular site.



Unbiased (Non-targeted) Sampling

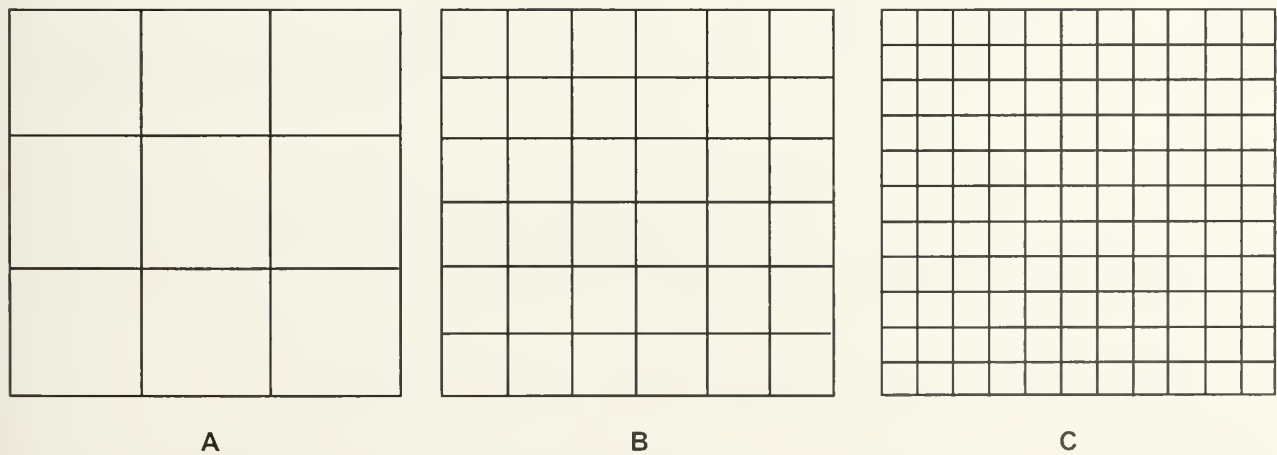
Unbiased, or non-targeted sampling is used when there are no obvious locations or features on a site that are favorable for the occurrence of asbestos. Although the term “unbiased” is often used in statistical data analysis, it is used in these Guidelines in the literal sense to note that a field sample is taken without geological bias. Such may be the case when rock outcrops are not present and depositional features from wind or water processes are not observed. Unbiased sampling is an appropriate sampling strategy when geologic evidence is insufficient to allow targeted sampling. Either spatially regular or spatially irregular sampling may be used.

Spatially Regular Sampling

This unbiased sampling approach involves sampling a site on a regular grid. The grid is sketched on the map used for the project as shown in Figure 6, A-C, and samples are collected at the grid intersections. Grid dimensions depend upon the desired resolution at which asbestos concentration will be characterized.

Many projects will not specify a resolution at which asbestos is to be characterized. In such cases, there may be geologic factors that can be used to design the grid. If different geologic units occur on the site, a grid may be designed so that each is sampled at least once. If water is a suspected depositional agent on site, a grid may be designed that samples all drainages, especially at obvious points of deposition. This concept could also be applied to wind deposition, and a grid designed that samples all points of suspected wind deposition.

Information regarding potential future use of the site may be used to define the grid. For instance, if the site is to be developed into a subdivision, the grid spacing may be equal to the average size of the parcels to be developed. Moreover, if the site is to be used for a hospital, school, or other structure of involuntary occupancy, a more conservative approach to grid design may be warranted compared to a site that is to be used for a paved parking lot.



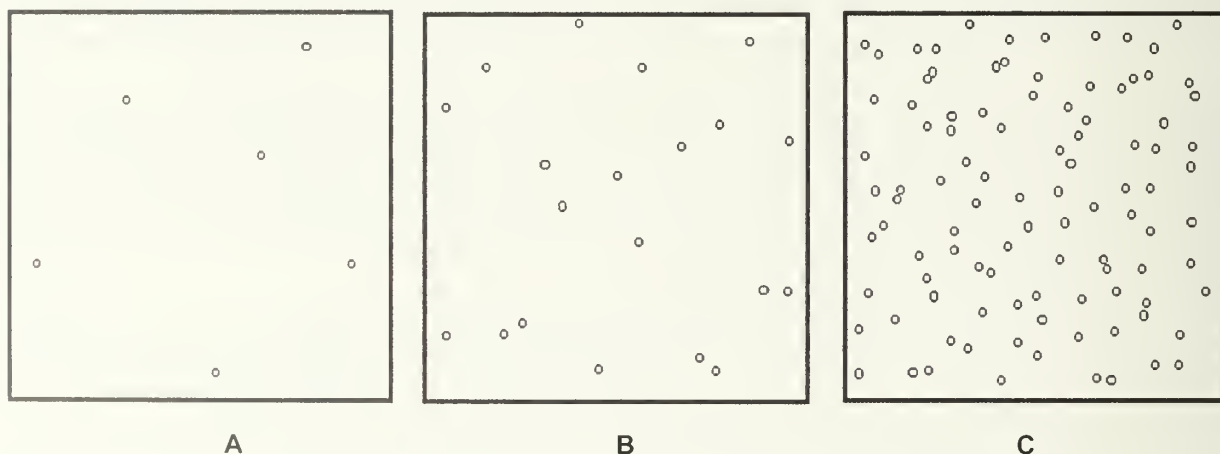
**Figure 6.** Three examples of regular grids are shown for a particular site. Samples are to be taken at grid line intersections, at intersections of lines and site boundary, and at the four corners of the site. Total samples to be collected for each grid are: A) 16; B) 49; and C) 169. Assuming the grids are superimposed on the same site, grid A represents the lowest resolution and grid C represents the highest resolution. Even though grid C represents highest resolution, it is not necessarily valid to say that it is a better choice than the other two grids.

One potential problem with sampling on a grid is that all of the potential sampling locations may not be physically accessible due to the topography, vegetation, or other physical barriers at the site.

### Spatially Irregular Sampling

This method does not use a pre-designed grid. Instead, the site investigator walks the site and collects samples, carefully noting the location of each sample on the site map. The resultant sampling pattern may look like that shown in Figure 7, A-C. Some samples may be clustered; others farther removed from neighboring samples. This is typical given varying physical characteristics on a site. As in the case of the figure showing a regular grid design, the figure showing irregular sampling is simply one example. It does not imply a rigorous guide for spatially irregular sampling. Choice of sampling location is left up to the site investigator.

Some investigators may use a random number generator to determine sampling locations. However, this approach may have the same problem of physical access to sample locations as does spatially regular sampling (grid sampling). As long as a site is sampled as thoroughly as possible spatially, it makes little difference where the samples are collected. In fact, a site investigator may sometimes be better able to sample a site for NOA using spatially irregular sampling. This is because geologic features associated with asbestos occurrence may be recognized and consequently sampled, even though the investigator is trying to sample in as unbiased a fashion as possible.



**Figure 7.** Three examples of spatially irregular sampling. Number of samples collected in each instance is: A) 6; B) 20; and C) 100. The number of samples taken depends primarily on site conditions and budgetary constraints and secondarily on intangible factors, such as regulatory requirements that may be imposed on the sampling. Even though situation C represents the largest number of samples, it is not necessarily valid to say that this group of samples is more representative of the site than are the other two groups.

### Spatially Regular Versus Spatially Irregular Sampling (Summary)

Spatially regular sampling has an advantage over spatially irregular sampling because the sampling density is uniform across the site and personal bias does not influence choice of sampling location. A possible disadvantage to this technique is the potential presence of physical barriers to sampling at some grid intersections because of the geomorphologic, botanical, and hydrological aspects of the site. However, spatially irregular sampling enables sampling around obstacles. Moreover, spatially irregular sampling may be accomplished more quickly because locating specific grid intersection

points on site is not necessary. As long as spatially irregular sampling covers a site as thoroughly as a spatially regular sampling approach would, each method should yield approximately the same quality of analysis.

### **Surface Sampling**

A surface sample is a sample of rock, soil or sediment obtained from the original ground surface, or at shallow depth, using hand tools. The term may also be applied in the sense of “current surfaces” such as the floor of an open pit or the exposure in a road cut. In this broader usage, the two examples just mentioned overlap with what might be considered “subsurface” samples. Surface sampling may be conducted using either a targeted or unbiased sampling strategy (see list of examples in the targeted sampling section). The potential for surface contamination from nearby grading or excavation activities should be considered when selecting sites for surface sampling. If possible, surficial samples should be collected before mechanized subsurface exploration or other on-site excavation or grading is done in order to minimize the possibility of surface contamination by newly exposed asbestos-containing materials.

### **Subsurface Sampling Considerations**

A subsurface sample is a sample obtained from, or that originated from, a location below the “original ground surface.” The need for subsurface samples and the depth of exploration should be determined in accordance with future use of the site. If the site is that of a single family dwelling, disturbance into the subsurface may only be to the depth of footings or to several feet in most instances. Other site uses may result in disturbance to a much greater depth and therefore require exploration and sampling to greater depths. Depending on the depth and extent of exploration and sampling required, trenching or drilling may be used to characterize the occurrence of asbestos in the subsurface. Because subsurface sampling is typically more difficult and costly than surface sampling, geologists should consider information and samples that may be obtainable from natural exposures such as gullies or previous site activities such as:

- Cuttings from a water well, and review of the Well Driller’s Report (Form DWR 188)
- Cuttings from utility pole or tower installation
- Material excavated by burrowing animals
- Existing cuts
- Existing fills
- Debris and cuttings from prior exploration efforts
- Exposures created by projects such as roads, pipelines, canals, tunnels, ditches, flumes, and utility trenches
- Exposures created by uprooted trees
- Exposures created by landslides
- Mine waste rock and tailings

Professional judgment should be applied regarding the use and significance of samples from the sources just listed because the place of origin of the subsurface materials may only be known within broad limits. Confidence levels as to sample validity should be described.



Opportunities for subsurface NOA sampling may be exploited at times when subsurface exploration is being carried out for other project purposes, such as basis of design. Exposures of the subsurface created by project exploration or construction activities may also provide the opportunity for direct observation and for subsurface sampling for asbestos. These include, for example:

- Exploratory excavations and borings for foundation design
- Exploratory excavations and borings for grading design
- Exploratory excavations and borings for pools, utility trenches, and underground storage facilities
- Exploratory excavations and borings for septic tank and leach field design
- Cut slopes and cut building pads during and after their excavation
- Trenches for foundation features such as footings
- Drilled holes for the placement of piles, piers, and grade beams
- Utility trenches during construction
- Excavations for pools and underground storage facilities during and after construction
- Cuttings from water wells

Both targeted or unbiased sampling approaches may be used in subsurface sampling. A sample of fibrous appearing vein material from a trench wall or a drill core would be an example of a targeted subsurface sample. A sample consisting of a crushed length of drill core obtained from drilling on a grid pattern would be an example of a regular unbiased sample. Vertical channel samples collected from several trenches on a property would mostly be irregular unbiased samples unless the trenches were located according to a regular pattern.

When selecting exploratory techniques and equipment for NOA investigations, methods should be selected that will prevent the loss or washing away of soft, weak, or friable forms of asbestos during exploration and sampling activities. Cossett and Delvaux (1979) discuss the use of core drilling in exploration for asbestos ore deposits and a review of their paper may be useful when planning drilling programs to evaluate non-ore asbestos occurrences. Consideration should also be given to selecting methods that minimize potential dispersal of NOA to the surrounding environment, either through airborne emissions, drilling fluids, or spoil piles. Many types of mechanical exploration and sampling equipment have the potential to spread asbestos, if encountered, through the atmosphere and to other parts of the site. Appropriate dust control measures should be applied whenever mechanical excavation equipment is utilized. Care should be taken that asbestos is not inadvertently carried onto or off of the site by vehicles or equipment. This transported asbestos could contaminate subsurface, surficial and atmospheric samples.

### **Field Test for Fibrous Minerals**

While definitive determination of a mineral material as fibrous or pseudofibrous requires laboratory testing, the following simple field test can provide information to assess which possibility is more likely. Such information may help in the selection of samples for laboratory analysis. The test requires a small mortar and pestle, some alcohol, and a hand lens.

Place a small amount of the fibrous appearing material in the mortar and cover it with alcohol. Crush the material with the pestle and observe it with a hand lens. If the sample is readily crushed to a powder it is not fibrous. If it formed separable needles or fibers, or matted together or formed a ball,



the material should be considered fibrous and may be asbestiform. The results need to be noted, and samples of material should be taken for confirmatory laboratory analysis.

### **Sample Collection**

There are a number of issues that should be discussed with the analytical laboratory staff prior to sampling, both for guidance and to determine if the use of certain procedures or materials is required. For example:

- Sample quantity - The quantity of rock, soil or sediment actually utilized for laboratory analysis is relatively small. Large samples may create problems for laboratories.
- Sample homogeneity - Is asbestos homogeneously distributed in the sample? Can the sample be processed to make it homogeneous? Are there specific parts of the sample being targeted for analysis?
- Sample processing requirements required for analysis - Will the asbestos laboratory complete all sample preparation or will some sample preparation, particularly crushing and pulverization activities, require involvement of another laboratory.
- Type of sample containers - Some laboratories prefer certain types of containers or may provide certain types of containers for asbestos samples; porous cloth and paper containers should be avoided.
- Procedures to prevent sample contamination - Use of single-use disposable sampling tools; cleaning procedures for multiple-use sample collection tools; procedures to avoid contaminating the outside of the sample container; bagging of sample containers to prevent cross contamination or spillage.
- Chain of Custody Procedures - Internal requirements for the project; regulatory requirements; laboratory requirements.
- Sample labeling - Unique and simple sample identification numbers; describe the sample in accordance with project Quality Assurance/Quality Control requirements.
- Quality Assurance/Quality Control - Submission of sample splits, field duplicate samples and blanks; submission of sample splits to a second laboratory for confirmatory analysis.
- Sample retention needs - Regulatory requirements; duration of retention; security and contamination prevention during retention; retaining party.
- Sample disposal requirements (at the end of the project or retention period).

Because asbestos is an airborne hazard, sample collection of geologic materials should not generate visible dust. If dust would be generated during sample collection, dampening of the sample with clean (asbestos-free) water should be considered. A squirt bottle of water may be useful for this purpose when collecting small volume samples by hand. The need for appropriate personal protective equipment during asbestos sampling should also be considered.

Before submitting samples to a laboratory for asbestos analysis, the investigator should review the internal Quality Assurance and Control Plan of the Laboratory, and to find out if the laboratory is accredited by the NIST/NVLAP or AIHA/IHLAP. NVLAP is the National Voluntary Laboratory Accreditation Program administered by the National Institute of Standards and Technology (NIST). This program requires biennial on-site inspections, participation in the NVLAP administered round-robin analysis of blind proficiency testing samples twice a year, self-administered round-robin sample

analyses with other laboratories, daily logs of quality control and random reanalysis of 10% of all samples. All participating laboratories receive detailed reports from NVLAP regarding their performance as indicated by the inspections and the NVLAP administered proficiency testing. These reports are required to be kept available for reference at the laboratory. IHLAP is the Industrial Hygiene Laboratory Accreditation Program administered by the American Industrial Hygiene Association (AIHA). The AIHA/IHLAP also offers accreditation programs and proficiency testing for laboratories performing asbestos analysis.

### **Sample Documentation**

Thorough sample documentation is necessary for the proper interpretation of analytical data. Particular information recorded for each sample at the time of collection may vary with the needs of the project. At a minimum, detailed sample location information must be recorded so that the exact sample location may be revisited, if necessary, and a clear, easy to use, sample-numbering system should be used. Detailed notes should be taken on the characteristics of the geology and soils at the sample site at the time of sample collection. Photographic documentation of the sample location may be considered. Appropriate Chain of Custody procedures should be followed. In addition to the information normally recorded, the following information may be particularly important for NOA investigations:

- Characteristics of any visible asbestos at the sample site (widths and orientations of veins, cross-fiber or slip-fiber veins, fibers on exposed slip-surfaces of serpentinite, fibrous rosettes of anthophyllite or chrysotile within the rock, etc.)
- Host rock characteristics and characteristics of related soils
- Potential natural fiber contaminants (local vegetation debris, animal hair, etc.)
- Likelihood that the sampled material originated on site
- Likelihood that the asbestos present is refined asbestos from a manufactured product or industrial process placed on site and is not local NOA (e.g., the on-site presence results from disposal activity, previous site activities, etc.)
- Likelihood that the NOA material has been transported from an off-site location of origin by natural processes (for example, down slope from an adjoining property)

## ANALYTICAL METHODS

### **Introduction**

As mentioned in previous sections, unequivocal identification of asbestos minerals requires information on morphology, chemical composition, and crystal structure. It is not the intent of these Guidelines to recommend one analytical method over another, but to introduce several analytical methods that may be applicable to soil and rock samples in NOA studies. The analytical methods chosen will depend on the goals and requirements of the particular study. In some cases, analytical methods may be dictated by regulatory requirements. Table 6 summarizes the various methods, the information they provide, and their advantages and disadvantages. Additional information on the application of these techniques can be found in Guthrie, (1993) and in the references included under each method.

The principal methods used by commercial asbestos laboratories to identify asbestos are polarized light microscopy (PLM) and transmission electron microscopy (TEM). PLM is commonly used to identify asbestos in bulk samples of manufactured materials such as insulation, and TEM is commonly used to identify asbestos in air monitoring samples collected from ambient air and occupational settings. TEM is also used to identify asbestos in water samples.

Phase Contrast Microscopy (PCM) is commonly used for monitoring asbestos in workplace atmospheres. However, PCM cannot distinguish between asbestos and non-asbestos fibers; it is only used where asbestos fibers are known to be in use and all fibers observed are assumed to be asbestos. The technique is not useful in identifying NOA and is not considered further in these Guidelines.

The physical and chemical properties of NOA in geologic samples are likely to be more complex and variable than asbestos encountered in manufactured products. Geologic samples may also contain asbestiform minerals other than the six types of asbestos commonly found in manufactured products. Additionally, the matrix of geologic samples is likely to be different and may be more variable than those in manufactured products. Some laboratories that routinely perform analysis of manufactured materials or air monitoring samples may not be as familiar with the analysis of geologic materials. Identification of asbestiform minerals in a geologic sample is relatively straightforward. Quantification of the amount of asbestiform minerals in a geologic sample is more difficult. Consequently, it is important that the geologist work closely with the laboratory to clearly define the analytical goals for the project.

Although most commercial asbestos laboratories should be able to perform asbestos analysis of geologic samples, many of them are not equipped to handle heavy-duty processing of rock samples (crushing, milling, size segregation, etc.). Thus, the physical presentation of the geologic sample to the laboratory becomes an important factor that ultimately may determine the outcome of the analysis. Good communication with the laboratory will help ensure that the analytical goals of the geological investigation are met and will also help the geologist gain an understanding of the analytical techniques used and their limitations. This will also lead to better planning of the field investigation.



Table 6. Summary Information on the More Common Analytical Techniques Applied to NOA Studies

Analytical Technique	Acronym	Information Provided	Comments	Sample Characteristics and Size
Polarized Light	PLM	The presence or absence and type of asbestos in a sample, and the particle morphology (asbestiform vs. non-asbestiform) can be determined. Estimation of the percent of asbestos (usually as area or particle percents) by visual or point counting methods is possible.	Used with thin-sections for rock-type characterization; used with grain mounts and immersion oils (dispersion staining) for mineral identification; grain mounts are better suited for asbestos identification than thin sections; difficult to use on very small particles - 1 micron practical resolution limit; relatively rapid and inexpensive compared to TEM asbestos methods.	Thin sections and mineral grains or particles.
Scanning Electron Microscopy	SEM	High magnification imaging of particle and fiber morphology. Qualitative or semi-quantitative chemical analysis of areas on individual mineral particles is possible if the SEM has EDS (energy dispersive spectroscopy) capabilities. Chemical composition information can be used for mineral identification.	High magnification imaging of mineral particle surfaces allows examination of smaller sized particles than PLM; chemical analysis by EDS is rapid but semi-quantitative and may not be sufficient for distinguishing different minerals with similar chemical compositions.	Sub-mm to 1 cm sized mineral particles and rock fragments. Particles with irregular surfaces may be utilized; sample surface may be coated with a thin layer of carbon or gold.
Electron Probe Microanalysis	EPMA	Quantitative chemical analysis of areas on individual mineral particles is possible. Chemical composition information can be used for mineral identification.	Utilizes WDS (wavelength dispersive spectroscopy) to provide quantitative results on major and minor elements; method requires good standard materials for high-quality quantitative analysis; method requires the sample to be flat and have a finely polished surface; excitation volume for elemental analysis is about 1-2 microns in diameter for standard EPMA; difficult to use on particles smaller than 5 microns; analysis of very small particles is not routine; some instruments may be equipped to provide SEM imaging and EDS semi-quantitative chemical analyses.	Sub-mm to cm sized mineral particles and rock fragments. Samples usually mounted as polished thin sections or polished epoxy-grain mounts; sample surface must be coated with a thin layer of carbon or gold.



Table 6 (continued). Summary Information on the More Common Analytical Techniques Applied to NOA Studies

Analytical Technique	Acronym	Information Provided	Comments	Sample Characteristics and Size
Transmission Electron Microscopy	TEM	High magnification imaging of particle morphology, semi-quantitative chemical analysis by EDS, and crystal structure information by Selective Area Electron Diffraction (SAED) can all be used to aid in positively identifying mineral grains and fibers. Some methods allow determination of asbestos percentages.	Slower and more complex to use than PLM for asbestos analysis but definitive for asbestos mineral identification. TEM may be used to analyze much smaller particles than can be analyzed by PLM and chemical analyses are of much smaller volumes than SEM or EPMA. TEM can be used for either qualitative or quantitative determination of the asbestos contents of samples.	Very small sample quantities may be analyzed; mineral particles must be thin enough (sub-micron) to allow electron beam transmission
X-ray Powder Diffraction	XRD	Identification of the major minerals type(s) present in bulk samples; may be used to estimate mineral abundance	Allows rapid determination of the major minerals present in a sample, provided there is not too much overlap between the different mineral diffraction patterns. The method has relatively high detection limits for minerals (typically in the percent to 10s of percent range, depending upon the mineral and the other minerals present) unless special sample preparation techniques are employed. No information is provided about morphology (asbestiform vs. non-asbestiform). This method has been used for quantitative determinations of asbestos abundance in samples but such determinations are not routine and require specialized procedures.	Sample must be powdered; about 0.1 to 1 g of sample are used for the analysis depending on the type of mounting method used.

Modified from Guthrie, 1993, pp. 262-265

## **Optical Microscopy**

Of the analytical techniques presented here, the application of polarized light microscopy is probably the most familiar to geologists. Optical techniques may be applied both to the description of thin sections for purpose of petrographic description and classification of rock samples and to grain mounts for identification of individual mineral grains using oil immersion methods. Discussion of the general techniques of optical mineralogy can be found in Nesse (1991) and Bloss (1999).

Examination of thin sections of rock samples by an experienced petrographer can provide information on rock-type, mineralogy, texture, alteration, and metamorphic grade – all of which may be useful in a NOA investigation. However, identification of asbestos minerals in thin section is difficult. Because individual asbestos fibers are much thinner than the thickness of the thin section, numerous fibers may overlap in a vein, or other minerals may underlie asbestos fibers. Either condition complicates the identification process. Consequently, grain mounts, rather than thin sections, are preferred for the identification of asbestos minerals. In grain mounts, it is possible to view grain boundaries and the splayed ends of fibers that are necessary to distinguish cleavage fragments from fibers.

Isolation in refractive index oil on a glass slide immediately distinguishes chrysotile (refractive index less than 1.57) from the amphibole-asbestos minerals (refractive indices above 1.59). However, this may not immediately separate the serpentine minerals from other potentially asbestiform minerals with refractive indices less than or equal to 1.57 such as palygorskite, sepiolite, brucite, or erionite. Nor will it exclude potentially asbestiform, non-regulated amphibole species that may have refractive indices greater than or equal to 1.59. The identification of the non-asbestiform serpentine minerals (chrysotile, lizardite, and antigorite) generally requires TEM or specialized X-ray diffraction methods. The amphibole asbestos minerals (tremolite, actinolite, anthophyllite, grunerite, and riebeckite) have distinctive optical properties in grain mounts, but the more rare cummingtonite and winchite may be confused with tremolite, and a chemical analysis may be needed to distinguish these minerals. More importantly, the fibular growth habit and common occurrence of {100} polysynthetic twinning typical of truly asbestiform amphiboles may result in near-parallel or parallel extinction, rather than the oblique extinction indicated in textbooks for non-asbestiform amphiboles. If accurate measurements of refractive indices are made, only two principal refractive indices may be found rather than the expected three (Verkouteren and Wylie, 2002). Consequently, it may be helpful to exploit gradations in grain-size and habit when trying to determine the optical properties of an amphibole.

For these reasons, identification of asbestos minerals by PLM should be performed in accredited laboratories by experienced microscopists who are familiar with the procedures used in asbestos analysis. The techniques used in laboratories specializing in asbestos identification are discussed in the following section.

## **Optical Microscopy for Asbestos Identification**

Most commercial laboratories that specialize in asbestos analysis of bulk materials and are accredited by NIST/NVLAP or AIHA/IHLAP should have staff microscopists capable of analyzing asbestos in geologic samples (rock, soil or sediment). These laboratories use polarized-light microscopy with dispersion staining (PLM/DS) for the routine identification or qualitative analysis of asbestos fibers in

grain mounts of bulk materials. This method allows determination of mineral habit and the following optical parameters: refractive index, pleochroism, birefringence, extinction angle, and sign of elongation. Dispersion staining is a technique using high-dispersion oils, which imparts bright colors to crystalline grains, that are indicative of the refractive index of the grain. Using color charts developed for this purpose, the microscopist is able to obtain an indirect measurement of the refractive index of the suspect asbestos fiber by matching the "staining" color (wave length), observed when the fiber is aligned in a particular optical orientation, with the corresponding refractive index read off the color chart (McCrone, 1987). PLM/DS analysis is low cost and widely available. It offers great sensitivity even at very low concentrations and the ability to generally differentiate the non-asbestiform and asbestiform habits of a mineral. No other analytical method offers all of these features. A limitation of the PLM/DS method is the size of fibers that can be resolved. Although modern optical microscopes can resolve fibers with diameters less than 1 micron using special illumination techniques, the practical resolution limit when using the PLM/DS method is somewhat greater than 1 micron (McCrone, 1987). Some individual asbestos fibers may have diameters smaller than this practical limit and, in a given sample, such fibers may not be observed or identified by this method. This may be of particular concern with soil samples where fiber size may have been reduced by chemical and physical weathering or by transport. In such cases, because of the small fiber size, PLM/DS may not adequately document the presence of asbestos in some soil samples. If small fibers are a concern, other methods such as scanning electron microscopy or transmission electron microscopy should be considered.

The analysis of a sample generally begins by performing a gross macro/microscopic examination of the sample using a simple stereomicroscope. For rock and soil samples this step is very important because it allows the analyst to assess the sample and to select specific areas of the sample for further analysis by PLM. Sub-samples of suspect fibrous components can be removed and prepared for analysis using PLM/DS (U.S. Environmental Protection Agency methods 600/M4-82-020, 1982 and 600/R-93/116, 1993). In some cases, the investigator may need to instruct the laboratory to search for asbestos fibers in specific areas of the sample, or submit only those portions of the mineral, rock or soil sample suspected to contain fibers that need confirmatory analysis. For example, the microscopist may not readily recognize inconspicuous cross-fiber veins in a rock sample.

In many geological investigations, qualitative analysis of a sample may be all that is needed to confirm the presence and identity of asbestiform minerals. If a quantitative measure of the concentration of asbestos in the sample is required using PLM, this is best accomplished by using a technique known as "point counting". This technique, which is best suited for the analysis of petrographic thin sections, can also be used on grain mounts and provides relatively accurate and precise estimates of the asbestos concentration (Perkins, 1990a). Using the polarized light microscope, point counting is a systematic procedure that involves traversing a microscope slide mount and recording the type of particle directly under the intersection of the reticle cross-hair or the points of a counting grid such as the 25-point Chalkley array. When used properly by experienced microscopists, point counting minimizes the strong bias that the analyst contributes to a simple visual estimation of the asbestos concentration. The U.S. Environmental Protection Agency (CFR, Title 40, Part 61, 1990, Asbestos NESHAP), for example, allows the challenge of visually estimated results reporting less than 10% asbestos. Friable asbestos-containing samples can then be re-analyzed using a point-counting method. Under this decision-making guideline, point-count results supersede visual estimation results. In California, the Air Resources Board developed a method (CARB Method 435, California



Environmental Protection Agency Air Resources Board, 1991) that uses point counting to estimate the asbestos concentration in quarried and crushed serpentinite. In New York state, the Department of Health's Environmental Laboratory Approval Program adopted the point-counting method as the method of choice to estimate the asbestos concentration in friable asbestos-containing materials (New York State Environmental Laboratory Approval Program Certification Manual for Asbestos, Method 198.1, 1997).

Two important practical considerations the investigator will face, when determination of the asbestos concentration in a geologic sample is required, are the type and quantity of sample to submit to the laboratory. Since the point-counting technique requires the sample to be homogenized prior to analysis, defining what is a "representative" sub-sample of the original sample becomes essential. For example, if the laboratory is presented with a 5-gallon bucket of rocks, how is the representative sample going to be defined? Even if the sample is just one fist-size rock that contains a cross-fiber vein, how much of the sample should the analyst take to homogenize? How does one ensure that accurate proportions of the different phases of the sample are included in the analysis? These are some of the practical analytical considerations that most methods and guidelines on point counting fail to address. Again good communication between the investigator and the laboratory staff will at least ensure that these important limitations and their ramifications are being considered.

The analytical sensitivity and precision of the point-counting method is determined by the total number of non-empty points counted in the analysis. Thus, a 400-point and a 1000-point analysis would yield analytical sensitivities of 0.25 (1 in 400) and 0.1 (1 in 1000) percent respectively. The analytical sensitivity and the overall precision of the analysis can be improved by either counting additional points or by attempting a gravimetric sample reduction to concentrate the fibrous phase of the sample. Typical gravimetric sample reduction techniques used for samples of manufactured materials include high temperature ashing and acid dissolution, heavy particle separation, and manual removal of large fibrous asbestos or non-asbestos sample components. Many of these methods may not be effective with geologic samples and their use will have to be evaluated on a case-by-case basis. For example, high temperature ashing may have very little effect on rock samples, but may be effective in reducing the organic components in soil samples. Some methods, such as acid dissolution must be used with care or the optical properties of chrysotile fibers may be altered by extended acid leaching (McCronc, 1987). It is important that the investigator selects a laboratory that shows demonstrated experience with these procedures if their use is anticipated.

Point counting is basically a systematic approach to determining the projected area of particles as viewed on a microscope slide. Thus, the asbestos concentration reported in units of area percent is not equivalent to the weight percent of asbestos present in the sample. Investigations have shown that the quality of point counting results is highly dependent on sample preparation (homogeneity, grain size uniformity, grain distribution on the microscope slide, etc.) and the specific gravity and concentration of asbestos fibers relative to the other sample components (Perkins 1990a, 1990b; Stewart, 1988). Studies at Research Triangle Institute (Perkins, 2000) and data accumulated from laboratory proficiency testing programs have shown that the concentration (expressed as area percent) of chrysotile asbestos determined by point counting tends to be lower than the true weight concentration while the concentration (expressed as area percent) of amphibole asbestos tends to be greater than the actual weight concentrations. Because of the effects of all these factors, point-counting results can exhibit great variability, especially when the true asbestos weight concentration is



under 10%. The statistical variability of point-count results for individual small representative sub-samples, for the total sample, or between samples can be determined, but it can be very challenging and costly. Therefore, it is essential that the need for quantitative data should be clearly defined as part of the planning phase of the site investigation before it is undertaken.

### **Scanning Electron Microscopy (SEM)**

SEM can be a powerful backup for optical microscopy because it allows much greater magnifications than optical microscopy and also allows semi-quantitative chemical analysis of the imaged material. Therefore, the SEM can be used to evaluate both the morphological and chemical composition of asbestiform minerals. The SEM produces images by scanning a finely focused beam of electrons across the surface of the sample. The interaction of the electron beam and the sample produces a variety of signals that can be used to image and chemically characterize the sample. Unlike PLM or transmission electron microscopy, the ability of the SEM to utilize reflected energy for imaging allows fibers adhering to other mineral surfaces to be easily observed. SEM images can provide a permanent record of grain sizes, shapes and aspect ratios, all of which are important to the characterization of asbestos minerals. Chemical analysis of specific areas of a sample can be accomplished using energy dispersive X-ray fluorescence spectrometry (EDS). This method utilizes characteristic X-rays of the elements in the sample generated at locations where the SEM electron beam strikes the sample surface. Elemental analysis of individual separated fibers and grains is ordinarily semi-quantitative but is often sufficient for mineral identification. Further information on the theory and application of the SEM and electron microprobe can be found in Potts (1987) and Goldstein and others (1981).

Because of the many advantages it offers, the SEM has been used for observation of asbestos fibers in a variety of matrices, e.g., mineral, bulk construction materials, and air and water. However, standard analytical methods for quantitative analysis of asbestos have been difficult to develop, primarily because of the difficulty in standardizing the many operating parameters that are controlled by the SEM microscopist. Thus, although some modern SEMs are capable of resolving surface features at the angstrom level, there is still much difficulty in obtaining adequate images of unit fibrils. Such images are necessary to perform quantitative analyses that use fiber measurements to estimate the volume and mass of each fiber, which are in turn used to derive a weight percentage of asbestos in the sample. Furthermore, although routine SEM/EDS analysis allows evaluation of sample morphology and provides semi-quantitative chemical data, it does not allow determination of crystal structure like Transmission Electron Microscopy. In addition to instrumental limitations, quantitative elemental analysis of suspect amphibole-asbestos fibers by SEM/EDS is difficult because of the variable composition of the amphiboles.

As a result of the work that the U.S. EPA is conducting in Libby, Montana, there is renewed interest in developing a standard quantitative analysis method for asbestos mineral samples using SEM/EDS. A method has been drafted and is currently undergoing validation (Remaley, 2002). This method relies on the direct transfer of an aliquot of the mineral sample (after sample preparation that includes size separation, and gravimetric reduction techniques) onto an SEM stub. Fiber lengths and diameters are recorded and estimations of the amount of asbestos are performed at several magnifications. These estimations are then integrated into a calculation that may also include a visual estimate by PLM of the amount of asbestos in the coarse portion of the original sample.

### **Electron Probe Microanalysis (EPMA)**

Electron microprobes are instruments designed specifically to produce quantitative elemental analyses of small point locations on a sample. Like the SEM, the electron microprobe uses a finely focused electron beam to analyze very small portions of the sample. In the electron microprobe, quantitative elemental analyses are obtained through the use of focusing wavelength-dispersive X-ray spectrometers and by optimizing the electron beam-sample-detector geometry by using flat, polished samples. In contrast, semi-quantitative elemental analysis by SEM/EDS utilizes energy-dispersive X-ray detectors and is usually performed on unpolished samples with irregular surfaces. Today, electron microprobes typically incorporate SEM imaging capabilities into their design and may be considered an alternative to the SEM. Imaging of sample surfaces in modern electron microprobes is almost as good as in an SEM. EPMA is utilized to obtain the quantitative elemental analyses needed for mineral identification and is routinely used for amphibole mineral identification in geologic research.

### **Transmission Electron Microscopy (TEM)**

The TEM is the ideal instrument for asbestos mineral identification in a dispersed sample because it allows a combination of high magnification imaging, selected area electron diffraction, and semi-quantitative EDS analysis. Unlike the SEM and electron microprobe, in which the electron beam interacts with the surface of the sample, in the TEM a very thin (typically < 0.15 micron for silicates) sample is used and the electron beam actually passes through the sample, hence the name Transmission Electron Microscope. In this sense, the SEM can be thought of as analogous to an optical microscope in reflected light mode and the TEM as analogous to an optical microscope in transmitted light mode. The TEM is the only instrument capable of imaging individual hollow-cored chrysotile fibers. Because TEMs are complex and expensive and extensive operator training is required to obtain and analyze TEM data, sample analyses by this method are more expensive than by PLM. However, the advantage of TEM is that it allows imaging and identification of much smaller diameter fibers than PLM. A review of the theory and application of the TEM can be found in Buseck (1992) and Potts (1987).

Like PLM and SEM, TEM may be used for visual estimates of a sample's asbestos content. As in SEM, semi-quantitative elemental analyses using EDS are also possible with the TEM. Additionally, it is possible to obtain information on the crystal structure of fibers in the TEM using Selective Area Electron Diffraction (SAED). SAED allows the crystal structure of individual fibers to be determined by electron diffraction. When the electron beam passes through the sample, the electrons are diffracted by the atomic structure of the mineral and, since each mineral has a unique crystal structure, the diffraction patterns produced are characteristic of that mineral. Because of its unique combination of analytical capabilities (high magnification imaging, semi-quantitative chemical analysis by EDS, and crystal structure determinations by SAED), use of the TEM for quantitative asbestos determinations is a principal interest today. As in the case of SEM, quantitative analytical methods for asbestos using the TEM have been difficult to develop. The best available guidelines are contained in the EPA Method for Analysis of Asbestos in Bulk Samples (U.S. Environmental Protection Agency, 1993 Method 600/R-93-116, Section 2.5). Based on these guidelines, some commercial laboratories have developed their own methods under the heading of "full-quantitative analysis of bulk samples by TEM."



In this method, a sample is reduced gravimetrically by any possible means that will separate the asbestos fibers from the matrix. This may involve physical particle separation by sieving, high temperature ashing and acid treatment (usually concentrated HCl) to remove the organic and acid soluble fractions of the sample. Depending on the nature of the sample, these techniques may or may not be effective in reducing the sample. Other gravimetric techniques may include decantation or flotation to separate the heavy particulate fraction, e.g., sand. The residue of the sample containing the asbestos fraction may be subjected to further particle size reduction or homogenization by grinding with a mortar and pestle or ball mill before being suspended in water. An aliquot of this suspension is deposited onto a filter membrane (mixed cellulose ester or polycarbonate). Several preparations at different dilution levels may have to be made to obtain an adequate sample suitable for analysis by TEM. Once dried, the sample is prepared for analysis using standard protocols (CFR, Title 40, Part 763, 1987, Asbestos-Containing Materials in Schools, AHERA).

Prepared TEM sample grids (usually a 3/8-in. diameter 200-mesh copper grid) are analyzed following the EPA Level II provisional method (Yamate and others, 1984), AHERA protocol, or ISO 10312 counting rules (International Organization for Standardization, 1995). The latter approach is preferred if the results of the analyses are to be used in risk assessment evaluations. The asbestiform particulates (particles having at least 3 to 1 length to width ratio) are counted and identified at a screen magnification of 15,000 to 20,000 times. Identification of asbestos is accomplished using morphology, selected area electron diffraction (SAED) and energy dispersive X-ray analysis (EDS). The mass of each asbestos fiber is calculated by multiplying the volume of the fiber (assumed to be a cylinder) by the density of asbestos ( $2.55 \text{ g/cm}^3$  for chrysotile, and  $3.3 \text{ g/cm}^3$  for amphiboles). A minimum of 10 grid openings or 100 asbestos structures are counted. Some protocols include rules for terminating the fiber counting procedure that attempt to account for fiber size distribution to ensure that the fiber counting effort is directed toward the population of fibers that contributes most to the mass of asbestos in the sample. The counting results are expressed in micrograms of asbestos per gram of sample or in weight percent. The analytical sensitivity of the analysis is usually calculated assuming a minimum number of fibrils of specific dimensions.

This quantitative TEM method has a clear advantage over semi-quantitative visual estimation methods by PLM, SEM or TEM in that the fraction of the sample used for analysis is representative of all the components of the sample that remain after gravimetric sample preparation. However, one needs to realize that the result of each analysis is based on the analysis of a very small amount of material so sample homogeneity is important. This fact has major implications on the expected variability of the results.

This quantitative TEM method is considered “state-of-the-art” by many, and it has the capability of achieving analytical sensitivities below 0.001% by weight, depending on the efficacy of the sample reduction techniques. However, the quality of the results ultimately is influenced by many factors that are not easily controlled from laboratory to laboratory and even within laboratories. From this point alone, one can expect that results will be highly variable. If quantitative analytical results are an important piece in the evaluation of the geological investigation, the investigator will need to give careful consideration to the issue of the variability of analytical results and its influence in the design of the sampling plan (e.g., minimum of number of samples, and the number of duplicate and replicate analyses that will be required to characterize a specific site).

Currently, there are no reliable means of comparing the quantitative results of the analyses obtained using the optical and electron microscopy methods outlined in these Guidelines. Thus, when quantitative results are needed, it is important that the investigator has a clear understanding of the intended use of the results so that the appropriate method of analysis is chosen. In some cases, the choice of method may be dictated by a regulatory requirement. As stated before, laboratory staff should be able to help the investigator with the selection of the most suitable analytical method and it is very important that this is done in the planning stage of the investigation.

### **X-ray Powder Diffraction (XRD)**

X-ray powder diffraction (XRD) is a widely used analytical technique for identifying minerals and characterizing their crystal structure. When an incident beam of X-rays strikes a sample of finely crushed mineral particles, the X-rays are scattered or diffracted in specific ways that relate to the atomic structures of the minerals present. Because each mineral, by definition, has a unique crystal structure, each mineral also has a corresponding unique X-ray diffraction pattern. These unique diffraction patterns can be compared with the diffraction patterns for rock, mineral or soil samples to determine the presence or absence of particular minerals. Sample preparation for XRD requires that the sample to be ground to the consistency of a fine powder. Generally, about 0.5 to 1 gram of sample is required for analysis, although as little as 10 milligrams of material may sometimes be adequate. The sample powder is not destroyed during the XRD process and may be retained for future reference if desired.

Mineral identification by X-ray powder diffraction works best for samples that are mono-mineralic or contain a small number of different minerals. Minerals must typically be present in at least several weight percent in a sample to be detected by XRD. If multiple minerals are present they should ideally have distinctly different reference patterns (i.e., limited or no diffraction peak overlaps). For example, a serpentine group mineral in a diffraction pattern is easily distinguished from an amphibole group mineral. However, correctly determining which serpentine or amphibole mineral is present may be difficult or impossible from XRD data alone because the diffraction patterns of minerals with closely related structures are very similar (O'Hanley, 1996, p. 65; Veblen and Wylie, 1993, p. 123; Wicks and O'Hanley, 1988, pp. 124-128). Distinguishing different amphibole species typically requires a chemical analysis in addition to XRD. Distinguishing among the serpentine minerals is complicated by the fact that many of the reference X-ray powder-diffraction patterns in common use over the last several decades for the serpentine minerals have recently been found to be inaccurate, misidentified, or of poor quality (Wicks, 2000). The reader is referred to Wicks (2000) for a thorough discussion of this issue and a list of accurate and inaccurate serpentine mineral powder-diffraction files.

It is sometimes possible to estimate the amounts of minerals present in a sample using XRD. Quantitative analysis by XRD requires complex special procedures and experienced personnel for reliable determinations. In some situations, such procedures may allow reliable determinations of mineral amounts below 1%. For additional information on quantitative analysis by XRD see Snyder and Bish (1989), Guthrie (1993) and Wilson (1987, pp. 86-94). Examples of quantitative XRD for asbestos can be found in Williams-Jones and others (2001, pp. 92 and 95) and in Addison and Davies (1990).



While XRD can be used to determine what minerals are present in a sample, it provides no information about the habit of those minerals. For example, if XRD indicates tremolite is present, there is no way to know from the diffraction pattern if the habit is prismatic or asbestiform. The determination of mineral habit must be done by visual examination of the tremolite (by unaided eye, optical microscope, SEM or TEM as necessary). Because of this limitation, the EPA recommends that XRD be used only to supplement quantitative estimates and that the presence of asbestos minerals indicated by XRD be confirmed with either PLM or TEM to insure that the asbestiform habit is present.

Additional information about X-ray powder diffraction methods and applications is available in a number of publications; only a few are listed here. Klein and Hurlbut (1993, pp. 275-288) provide an overview of X-ray crystallography including an introduction to X-ray powder diffraction. A rigorous discussion of all aspects of X-ray powder diffraction can be found in Bish and Post (1989). Wilson (1987) contains a less rigorous, but useful detailed overview of XRD. Middleton (1979, pp. 264-269) discusses the application of XRD to asbestos mineral identification.

### **Other Analytical Techniques** (Research methods, not routinely applied to NOA site investigations)

The following are specialized techniques that may have application in certain research projects for asbestos, serpentine minerals, or other associated minerals. They should not be considered routine methods for site evaluation work at this time, although they may have application in follow-up detailed studies. None of these techniques can differentiate between asbestiform and non-asbestiform habits of the same mineral. These techniques will only be briefly discussed here. Additional details about these techniques and their applications are available in the listed references.

### **Microbeam X-ray Diffraction**

The microbeam X-ray diffraction camera allows the non-destructive identification of fine-grained minerals in a thin section by X-ray diffraction. This technique permits XRD data to be compared directly with the optical characteristics of the minerals in-situ in a thin section. Additionally, the polytype of the mineral or minerals present can be determined. For additional information on application of this technique to the study of serpentinites see Wicks and O'Hanley (1988, p. 131), Wicks and Zussman (1975), and O'Hanley (1996, pp. 62-65).

### **Single Crystal Diffraction and Fiber Diffraction**

Single crystal diffraction methods are used in the detailed study and description of crystal structures. Single crystal diffraction has been applied to the study of lizardite and antigorite (see Wicks and O'Hanley, 1988, pp. 128-129). Fiber diffraction has been used to study fibrous and splintery serpentine minerals, chrysotile, polygonal serpentine and antigorite (see Wicks and O'Hanley, 1988, pp. 129-130).

### **Infrared Spectroscopy (IR Spectroscopy or Spectrometry)**

Infrared Spectroscopy (IR) can be used to identify minerals and, in some cases, to determine mineral abundances quantitatively. The absorption of infrared radiation by minerals depends upon atomic masses of the constituent atoms and on the lengths, strengths and force of interatomic bonds in a

mineral's structure. It is also constrained by the overall symmetry of the unit cell and the local site symmetry of each atom within the unit cell. Crystalline order, and particle size, shape and orientation relative to the beam of infrared radiation also influence the infrared radiation absorption spectrum. These effects work together to produce infrared spectra that are unique for a number of different minerals. These reference infrared spectra can be compared with the infrared spectrum of an unknown sample to determine the likelihood of the presence or absence of particular minerals. For a more detailed discussion of the IR method applied to asbestos see Middleton (1979, pp. 260-264). Additional information on IR applications for minerals may be found in Wilson (1987), and in McMillan and Hofmeister (1988).

Chrysotile and antigorite infrared spectra are significantly different and readily distinguished from each other. These serpentine minerals can also be easily differentiated from clays by their characteristic absorption bands. Consequently, this technique may have application in studies to document the presence or absence of chrysotile in soil and sediment samples. Quantitative determinations of minerals, including asbestos, by IR is sometimes possible (see Coates, 1977).

#### **Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and Field Portable IR Spectrometer (Experimental)**

The U.S. Geological Survey is currently investigating the application of AVIRIS as a remote sensing method for identifying areas containing asbestos minerals. In 1997, imaging spectroscopy data were collected over a small portion of the Sierra Nevada foothills in California and processed using a U.S. Geological Survey spectral mapping algorithm called Tetracorder (Swayze and Ashley, 2001). Outcrops of chrysotile and antigorite bearing serpentinite and several outcrops of tremolite and talc bearing schists along a major fault zone were revealed on maps of the 2-2.5 micron reflectance spectral region produced by this technique. Because AVIRIS is an airborne spectral method, dense vegetation may limit its ability to provide information on the surface mineralogy of soil and rock exposures. Where surface vegetation is dense, it may be possible to map the boundaries of serpentinite and ultramafic rock areas by vegetation reflectance characteristics. As part of this work, the U.S. Geological Survey is also currently investigating the ability of a portable IR spectrometer to detect and identify asbestos minerals in the field. Although these methods are experimental at this time, they may eventually become viable tools for identifying and mapping NOA.

#### **Differential Thermal Analysis (DTA)**

Differential Thermal Analysis (DTA) measures the heat evolved (exothermic reactions) or absorbed (endothermic reactions) by a sample during heating. DTA data thus reflect changes in the thermal properties of the sample. These data can indicate the occurrence of a wide range of reaction types such as solid-state phase changes, decomposition reactions and the removal of sorbed species. This method has been commonly used with X-ray diffraction to study clay minerals and has been applied to the study of serpentine minerals. Both antigorite and chrysotile have a strong endothermic peak at about 700°C and a sharp strong exothermic peak at about 830°C (Hutchison, 1974, p. 457). For additional information on the general application of this method to minerals, see Wilson (1987). Hodgson (1979, pp. 94-106) contains information on thermal decomposition reactions for amphibole and chrysotile asbestos minerals.

## GLOSSARY

**Acicular:** Refers to “crystals that are extremely long and thin and have a small diameter. (An acicular crystal is a special type of prismatic crystal. A prismatic crystal has one elongated dimension and two other dimensions that are approximately equal.) As defined by the American Geological Institute (1980), a mineral fragment must be at least three times as long as it is wide to be called acicular. Acicular crystals or fragments are not expected to have the strength, flexibility, or other properties of asbestiform fibers.” (National Research Council, 1984)

**Actinolite:** A calcic amphibole having the formula  $\text{Ca}_2(\text{Mg}, \text{Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Actinolite sometimes crystallizes in the asbestiform habit and is one of the regulated asbestos minerals.

**Albitite:** A porphyritic igneous rock with albite phenocrysts in a predominantly albite groundmass. Accessory minerals may include muscovite, garnet, apatite, quartz, and opaque oxide phases.

**Aliquot:** A representative portion of a sample taken for analysis.

**Amosite:** A commercial term for cummingtonite-grunerite asbestos.

**Anthophyllite:** A Fe-Mg-Mn-Li amphibole having the formula  $(\text{Mg}, \text{Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Anthophyllite sometimes crystallizes in the asbestiform habit and is one of the regulated asbestos minerals.

**Antigorite:** A serpentine group mineral having a formula close to  $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ . Small amounts of  $\text{Fe}^{2+}$  may substitute for Mg in antigorite.

**Apparent fiber:** A term applied to single crystals or polycrystalline aggregates that have a fibrous appearance but are not composed of separable fibers. The fibrous appearance may be the result of oscillatory crystal growth, twinning, or pseudomorphic replacement of another fibrous mineral.

**Asbestiform:** “The unusual crystallization habit of a mineral when the crystals are thin, hair like fibers. Historically, the definition of asbestiform habit was based primarily on appearance, and the properties were only implied. At present, the definition of asbestiform habit is often augmented to include a statement on the properties of asbestiform fibers, i.e., shape; enhanced strength, flexibility, and durability; diameter-dependent strength; and unique surfaces. The fibers of asbestos are good examples of the asbestiform habit.” (National Research Council, 1984)

**Asbestos:** The term asbestos is used to identify a group of six commercially important silicate minerals of fibrous or asbestiform habit having properties of high tensile strength, flexibility, chemical resistance, and heat resistance. These properties have made these minerals useful in many manufactured products and industrial processes during the twentieth century. The six types of asbestos are chrysotile, crocidolite (asbestiform riebeckite), amosite (asbestiform cummingtonite-grunerite), asbestiform tremolite, asbestiform actinolite, and asbestiform anthophyllite. The term is also sometimes used for manufactured products containing one of these six minerals.

**Asbestosis:** A diffuse fibrous scarring of the lungs.



**ASTM:** American Society for Testing and Materials

**AVIRIS:** Airborne Visible/Infrared Imaging Spectrometer. (See page 50)

**Bronchogenic carcinoma:** Lung cancer.

**Chalkley array:** An eyepiece reticle used in point counting to quantify asbestos in bulk samples.

**Chrysotile:** A serpentine group mineral having the formula  $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ . Chrysotile can crystallize in both asbestiform and non-asbestiform habits but commonly crystallizes in the asbestiform habit. Chrysotile is one of the regulated asbestos minerals.

**Cleavage:** Cleavage refers to the preferential splitting of crystals along planes of structural weakness (cleavage planes).

**Clinochrysotile:** A monoclinic polytype of chrysotile.

**Crocidolite:** A varietal term used in the past for riebeckite-asbestos.

**Cross-fiber:** A descriptive term applied to veins of fibrous minerals when the fibers are perpendicular to the walls of the vein.

**Cummingtonite:** A Fe-Mg-Mn-Li amphibole having the formula  $(\text{Mg,Fe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ . It is part of the Cummingtonite-Grunerite series. Cummingtonite sometimes crystallizes in the asbestiform habit and is one of the regulated asbestos minerals.

**DTA:** Differential thermal analysis. (See page 50)

**Dispersion staining:** A microscopy technique using high-dispersion oils, which imparts bright colors to crystalline grains, that are indicative of the refractive index of the grain.

**EMPA:** Electron probe microanalysis. (See page 46)

**Erionite:** A zeolite group mineral with the formula  $\text{K}_2(\text{Na,Ca}_{0.5})_8[\text{Al}_{10}\text{Si}_{26}\text{O}_{72}]\cdot 30\text{H}_2\text{O}$ . Erionite may crystallize in the asbestiform habit.

**Fibril:** An individual fiber of asbestos, usually a single crystal.

**Fibrous:** (National Research Council, 1984) refers to “(1) single crystals that resemble organic fibers such as hair or cotton and (2) large crystals or crystalline aggregates that look like they are composed of fibers (i.e., long, thin, needlelike elements) (Dana and Ford, 1932). The apparent fibers do not need to be separable. If the fibers are separable and are strong and flexible, they are asbestiform. If they have the normal strength and brittleness of the mineral, they are acicular.”

**Grunerite:** A Fe-Mg-Mn-Li amphibole having the formula  $(\text{Fe,Mg})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$ . It is part of the Cummingtonite-Grunerite series. Grunerite sometimes crystallizes in the asbestiform habit and is one of the regulated asbestos minerals.

**Habit (or Crystal Habit):** Habit is the actual shape assumed by a crystal or aggregate of crystals. Habit does not imply either a particular crystal structure or chemical composition. Many minerals, including the asbestos minerals, crystallize in a variety of habits depending on the environment in which the mineral forms.

**IR:** Infrared spectroscopy or infrared spectrometry. (See page 49)

**Lizardite:** A serpentine group mineral with the formula  $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ . Lizardite is one of the rock forming serpentine minerals.

**Mass Fiber:** Mass fiber asbestos consists of randomly orientated fibers and may have an appearance quite different from cross-fiber or slip-fiber asbestos. Mass fiber asbestos has sometimes been referred to as “Mountain Leather” or “Mountain Cork” because of its appearance.

**Mesothelioma:** A rare cancer of the thin membranes lining the lungs, chest, and abdominal cavity.

**Mountain Cork:** A variety of asbestos consisting of interlaced fibers and resembling cork. A term used for mass fiber asbestos.

**Mountain Leather:** A variety of asbestos consisting of interlaced fibers and occurring in thin tough sheets. A term used for mass fiber asbestos.

**Orthochrysotile:** An orthorhombic polytype of chrysotile.

**Parachrysotile:** A polymorph of chrysotile.

**Pericardial:** Pertaining to the membrane that surrounds the heart.

**Peritoneal:** Pertaining to the membrane that lines the abdominal cavity.

**Picrolite:** The term “picrolite” describes a vein-filling serpentine mineral that is typically pale yellow to apple green in color, and that may be either massive or pseudofibrous in habit. Because picrolite may be lizardite, chrysotile, antigorite, or a mixture of these minerals the term does not denote a particular mineral species but is a useful field term.

**Pleural:** Pertaining to the membrane that lines the cavities containing the lungs.

**Pleural Plaques:** Localized fibrous scars lining the space surrounding the lungs.

**Polymorph:** Minerals that have the same chemical composition but different crystal structures are called polymorphs. For example, diamond and graphite are polymorphs.

**Polytype:** A term used for polymorphs that have the same chemical composition but differ in the stacking sequence and orientation of the layers of atoms that make up the structure.

**Pseudofiber:** A term applied to single crystals or polycrystalline aggregates that have a fibrous appearance but are not composed of separable fibers. The fibrous appearance may be the result of oscillatory crystal growth, twinning, or pseudomorphic replacement of another fibrous mineral.

**Riebeckite:** A sodic amphibole having the formula  $\text{Na}_2(\text{Fe}^{2+}_3, \text{Fe}^{3+}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Riebeckite sometimes crystallizes in the asbestiform habit and is one of the regulated asbestos minerals. It is sometimes referred to by the varietal name crocidolite when asbestiform.

**Rodingite:** Rodingite is a calc-silicate rock that typically contains hydrogarnet, diopside, idocrase, and chlorite. Rodingites are formed by metasomatism of gabbros or basalts and typically occur as inclusions within serpentinites.

**SAED:** Selective area electron diffraction. (See page 46)

**SEM:** Scanning electron microscopy or scanning electron microscope. (See page 45)

**Serpentine:** A mineral group. The serpentine group minerals are phyllosilicates having the general chemical formula  $\text{A}_{2-3}\text{Si}_2\text{O}_5(\text{OH})_4$ . The rock forming serpentine group minerals are lizardite, chrysotile, and antigorite.

**Serpentinite:** A rock consisting almost entirely of one or more of the serpentine minerals (lizardite, chrysotile, and antigorite). In addition to serpentine minerals, small amounts of other minerals such as magnetite, chromite, talc, brucite, or tremolite-actinolite may be present.

**Slip-fiber:** A descriptive term applied to veins of fibrous minerals when the fibers are oriented approximately parallel to the vein walls.

**TEM:** Transmission electron microscopy or transmission electron microscope. (See page 46)

**Tremolite:** A calcic amphibole having the formula  $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Tremolite sometimes crystallizes in the asbestiform habit and is one of the regulated asbestos minerals.

**Ultramafic Rock:** Ultramafic rocks are igneous rocks such as peridotite, dunite, pyroxenite, and hornblendite that contain greater than 90% of olivine, pyroxene or hornblende (International Union of Geological Sciences, 1973; Le Maitre, 1989; Le Bas and Streckeisen, 1991). "Ultramafic" is also a chemical term that is applied to rocks such as peridotite, dunite, pyroxenite, and serpentinite.

**Winchite:** A sodic-calcic amphibole having the formula  $(\text{Ca}, \text{Na})(\text{Mg}_4\text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2$ . Winchite sometimes crystallizes in the asbestiform habit.

**XRD:** X-ray diffraction. (See page 48)



## APPENDIX A

### **Health and Safety Considerations in Conducting Naturally Occurring Asbestos Investigations**

These Guidelines do not purport to address the safety issues associated with conducting geological investigations for NOA. It is the responsibility of the user of these Guidelines to establish appropriate health and safety practices and to determine the applicability of any regulatory limitations prior to initiating a NOA investigation.

Asbestos fibers in a geological setting are not inherently hazardous to humans if they are left undisturbed. Asbestos fibers may cause adverse health effects including asbestosis, lung cancer and mesothelioma after long latency periods if the fibers become airborne and are inhaled. A large number of occupational studies have reported the occurrence of significant health effects by occupational exposure to asbestos via inhalation. Different exposure-response relationships by workforce may be in part explained by the fiber type, particle size and industrial process.

Individuals involved in geologic investigations of NOA should be aware of the potential health hazards associated with asbestos exposure and take appropriate measures to avoid exposure. As in any field study, appropriate health and safety measures should be planned and followed. Whenever contact with asbestos-containing material is possible (e.g., drilling, sampling, construction), a health and safety plan should identify potential hazards and outline the procedures to be followed to avoid exposure.

Geological investigators should become familiar with the policies, regulations, and federal, state and local government requirements for health and safety procedures related to asbestos exposure. Numerous safety and environmental laws are enforced by federal, state, and local governments. The four major federal health and safety regulators are the U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) and Mine Safety and Health Administration (MSHA); the U.S. Environmental Protection Agency (EPA); and the U.S. Department of Transportation (DOT).

- OSHA policies are found in the *U.S. Code of Federal Regulations* (CFR) Title 29—Labor, parts 1900-1910 (U.S. Department of Labor, 1995). This volume defines general industrial safety requirements.
- MSHA policies are found in the *U.S. Code of Federal Regulations* (CFR) Title 30 (U.S. Department of Labor, 2002).
- EPA policies are described in the *U.S. Code of Federal Regulations* (CFR) Title 40 (U.S. Environmental Protection Agency, 1995).
- DOT policies are found in the *U.S. Code of Federal Regulations* (CFR) Title 49 (U.S. Department of Transportation, 1995). DOT regulates transportation of hazardous materials by authority of the Hazardous Materials Transportation Act

Geologists performing or supervising NOA investigations should be aware of the requirements for worker health and safety related to potential exposure to asbestos (U.S. Department of Labor, 1995, CFR, Title 29—Labor, parts 1900-1910). In California, these regulations are administered by the California Department of Industrial Relations, Division of Occupational Safety and Health. More information can be found at the DOSH asbestos web page at <http://www.dir.ca.gov/dosh/Asbestos.html>.

General guidance on health and safety issues and practices for geologic field investigations are described in *A Guide to Safe Field Operations* (Yobbi and others, 1996), *Safety in Field Activities* (Lane and Fay, 1997), and *Planning for Field Safety* (American Geological Institute, 1992). Additional safety requirements can be found in U.S. Geological Survey Handbook 445-2-H, *USGS Occupational Safety and Health Program Requirements Handbook* (U.S. Geological Survey, December 2000).

## APPENDIX B

### Summary of Asbestos Regulations

The following discussion is adapted from the California Air Resources Board Staff Report: *Initial Statement of Reasons for the Proposed Asbestos Airborne Toxic Control Measure for Construction, Grading, Quarrying, and Surface Mining Operations, June 8, 2001*. (<http://www.arb.ca.gov/regact/asbesto2/isor-short.pdf>)

Asbestos emissions in California are regulated at the federal, state, and local levels. Through its program for hazardous air pollutants, the U.S. EPA promulgated regulations for asbestos milling activities, the manufacture of asbestos products, demolition and renovation activities, and waste-disposal operations. Both California and federal regulations exist covering the transport of asbestos and asbestos-containing waste material. The U.S. EPA has also promulgated the Asbestos Hazardous Emergency Response Act (AHERA), which provides a framework for dealing with asbestos in schools. In 1990, the U.S. EPA adopted a ban on most of the remaining uses of asbestos in commercial products. The federal Occupational Safety and Health Administration (OSHA) and the Mine Safety and Health Administration (MSHA) regulate workplace practices and set maximum asbestos exposure levels for workers. In 2000, the U.S. EPA extended occupational standards of OSHA to cover state and local government employees and employees of the public schools. Also, the federal Consumer Product Safety Commission regulates the use of asbestos in consumer products. California has an airborne toxic control measure (ATCM) restricting the use of ultramafic rock or serpentine rock for surfacing applications (Title 17, CCR, Section 93106). In July 2001, a new ATCM for construction, grading, quarrying, and surface mining operations was adopted that will regulate grading and excavation activities in areas of serpentine or ultramafic rocks. This ATCM became effective November 19, 2002.

### **Federal Statutes & Regulations**

#### National Emissions Standards for Hazardous Air Pollutants

In 1973, asbestos was included as a hazardous air pollutant under the National Emissions Standards for Hazardous Air Pollutant (NESHAP) regulations. The Asbestos NESHAP was intended to minimize the release of asbestos fibers during activities involving commercial handling of asbestos. The commercial sources covered by the asbestos NESHAP are as follows:

- Asbestos mills
- Asbestos mine tailings for roadways
- Manufacturing asbestos products
- Demolition and renovation
- Spraying asbestos
- Fabricating
- Insulating materials
- Waste disposal
- Active and inactive waste disposal sites



The NESHAP requires that there be no visible emissions, that the asbestos-containing material must be adequately wet, and specifies packaging, transport, and disposal procedures. Record keeping and training are also required under the NESHAP regulations. Only asbestos-containing material with an asbestos content greater than 1% is covered by these regulations.

### National Pollutant Discharge Elimination System

The U.S. EPA has promulgated a National Pollutant Discharge Elimination System (NPDES) storm water program (Phase I); 40 C.F.R. Part 122, 123, 124 to address water discharges from industrial, municipal, and construction activities. NPDES recognizes asbestos as a toxic pollutant and as a hazardous substance. Quarries and surface mines are covered under the industrial section of the NPDES regulation. The construction section applies to construction sites that disturb 5 acres or more. Phase II of NPDES (40 CFR Part 122, Subpart B, Section 122.26 et seq.) goes into effect March 10, 2003 and reduces the size of the covered construction activity to 1 acre. NPDES provides that discharges of storm water to waters of the United States from industrial, municipal, and construction projects are effectively prohibited unless the discharge is in compliance with a state issued NPDES permit. The NPDES permit requires all industrial, municipal, and construction dischargers to develop and implement a Storm Water Pollution Prevention Plan that specifies Best Management Practices (BMPs) that will prevent all pollutants (including soil) from contacting storm water with the intent of keeping all products of (wind and water) erosion from moving off-site into receiving waters.

### Asbestos Hazard Emergency Response Act

The AHERA was enacted in 1986 to address asbestos hazards in schools. The goal of AHERA was to protect students, teachers, and staff from friable asbestos-containing building materials. The AHERA regulations cover inspection, appropriate response actions, and periodic surveillance of asbestos-containing building materials used in schools.

### Toxic Substances Control Act

The Toxic Substances Control Act (TSCA) of 1976 was enacted by Congress to give the U.S. EPA the ability to track the 75,000 industrial chemicals currently produced or imported into the United States. One of these substances is asbestos. The U.S. EPA repeatedly screens these chemicals and can require reporting or testing of those that may pose an environmental or human-health hazard. The U.S. EPA can ban the manufacture and import of those chemicals that pose an unreasonable risk. The U.S. EPA used TSCA in 1989 to ban the use of asbestos in manufactured commercial products. Most of this ban was vacated by the United States 5<sup>th</sup> Circuit Court of Appeals in 1991 and the rule was remanded to the U.S. EPA. The U.S. EPA has not yet re-issued this rule.

### Vehicle Code

Federal and California vehicle codes cover the transportation of hazardous substances and hazardous waste. The definition of hazardous substances is lengthy and contained in Title 49, Section 172.101 of the Code of Federal Regulations and California Vehicle Code Section 2452. Asbestos is classified as a hazardous substance. The California Vehicle Code has additional regulations on spillage on highways.

### Occupational Safety and Health Administration (U.S. Department of Labor)

The purpose of OSHA is to save lives, prevent workplace injuries and illnesses, and protect the health of all America's workers. OSHA has regulations covering asbestos exposure in general industry and construction. These regulations set standards for a maximum exposure limit and include provisions for engineering controls and respirators, protective clothing, exposure monitoring, hygiene facilities and practices, warning signs, labeling, record keeping, and medical exams.

OSHA has a time-weighted permissible exposure limit and an excursion limit standard. The time-weighted average (averaged over an 8-hour period) permissible exposure limit is set at 0.1 fibers per cubic centimeter (f/cc). An excursion limit, averaged over a 30-minute period, is set at 1.0 f/cc. Both of these standards are called permissible exposure limits or PEL's.

### Asbestos Worker Protection

The U.S. EPA promulgated the Asbestos Worker Protection Regulation (AWPR) to protect state, local government, and public education employees from the health risks of exposure to asbestos to the same extent as private sector workers. The AWPR asbestos standards are set at the same level as the asbestos standards of OSHA. The AWPR covers employees who are performing construction work, custodial work, and automotive brake and clutch repair work.

### Mine Safety and Health Administration

MSHA administers the provisions of the Federal Mine Safety and Health Act of 1977 and enforces compliance with mandatory safety and health standards. MSHA has notified mine operators that they must ensure that asbestos-containing ore or rock is identified and measures are in place to protect miners from overexposure to asbestos-containing dust. MSHA requires operators to determine if the rock or ore contains asbestos. If it does, operators are to have a plan in place to ensure that miners are protected from dust containing asbestos. Miners cannot be exposed to more than two fibers per cubic centimeter of air for an 8-hour work shift.

## **State Asbestos Statutes, Regulations, and Guidance**

### Identification of Asbestos as a Toxic Air Contaminant

In March 1986, the California Air Resources Board (CARB/Board) identified asbestos in accordance with Health and Safety Code (H&SC) Section 39650, et seq. as a toxic air contaminant (TAC). The Board identified the following mineral forms of asbestos as a TAC: chrysotile, actinolite, amosite, anthophyllite, crocidolite, and tremolite. The Board concluded there was not sufficient scientific evidence available to identify a threshold exposure level for asbestos below which no significant adverse health effects are anticipated (Title 17, California Code of Regulations, Section 93000). The United States Environmental Protection Agency (U.S. EPA) has also listed asbestos, in all its forms, as a hazardous air pollutant pursuant to Section 112 of the Federal Clean Air Act.

State regulations on asbestos are related to demolition and renovations, and waste disposal of asbestos-containing material. California also has a statewide regulation covering naturally occurring asbestos. The Asbestos ATCM for Asbestos-Containing Serpentine, adopted in 1990, prohibited the use of serpentine aggregate for surfacing if the asbestos content was 5% or more asbestos. This ATCM was modified in July 2000 to include ultramafic rock and the asbestos content threshold was lowered to 0.25 percent. The modified asbestos ATCM became effective November 13, 2001.

In July 2001, CARB adopted a new ATCM for construction, grading, quarrying, and surface mining operations that regulates grading and excavation activities in areas of serpentine or ultramafic rocks. This ATCM became effective November 19, 2002. More information about these regulations can be found at <http://www.arb.ca.gov/toxics/asbestos.htm>.

In October 2000, the Governors Office of Planning and Research issued a memorandum providing guidance to Lead Agencies in analyzing the impacts of naturally occurring asbestos on the environment through the California Environmental Quality Act (CEQA) review process (the memorandum is available at <http://www.opr.ca.gov/clearinghouse/asbestos.shtml> ).

In November 2000, the California Department of Real Estate added questions to some of its subdivision forms related to the naturally occurring asbestos on property proposed for development.

In addition to these requirements, many counties also have ordinances or requirements related to the use of asbestos-containing materials as surfacing or to excavation and grading in areas likely to contain naturally occurring asbestos. The geologist should always be aware of any local ordinances or requirements when performing investigations for naturally occurring asbestos.



**APPENDIX C****Sources of Soil Maps**

Natural Resources Conservation Service  
430 G Street (no. 4164)  
Davis, CA 95616-4164

California Department of Forestry and Fire Protection  
6105 Airport Road  
Redding, CA 96002  
<http://www.fire.ca.gov>

Forest Supervisors Office - 18 National Forests in  
California with separate offices.  
<http://www.r5.pswfs.gov/forest-offices.html>

**Angeles National Forest**  
701 North Santa Anita Avenue  
Arcadia, CA 91006  
626-574-1613

**Cleveland National Forest**  
10845 Rancho Bernardo Road  
Rancho Bernardo, CA 92127-2107  
858-674-2901

**El Dorado National Forest**  
100 Forni Road  
Placerville, CA 95667  
530-622-5061

**Inyo National Forest**  
873 North Main Street  
Bishop, CA 93514  
760-873-2400

**Klamath National Forest**  
1312 Fairlane Road  
Yreka, CA 96097  
530-842-6131

**Lake Tahoe Basin Management Unit**  
870 Emerald Bay Road, Suite 1  
South Lake Tahoe, CA 96150  
530-573-2600

**Lassen National Forest**  
2550 Riverside Drive  
Susanville, CA 96130  
530-257-2151

**Los Padres National Forest**  
6755 Hollister Ave., Suite 150  
Goleta, CA 93117  
805-968-6640

**Mendocino National Forest**  
875 N. Humboldt  
Willows, CA 95988  
530-934-3316

**Modoc National Forest**  
800 West 12th Street  
Alturas, CA 96101  
530-233-5811

**Plumas National Forest**  
P.O. Box 11500  
159 Lawrence Street  
Quincy, CA 95971  
530-283-2050

**San Bernardino National Forest**  
1824 Commercenter Circle  
San Bernardino, CA 92408-3430  
909-884-6634

**Sequoia National Forest**  
900 West Grand Avenue  
Porterville, CA 93257  
559-784-1500

**Shasta-Trinity National Forest**  
2400 Washington Avenue  
Redding, CA 96001  
530-244-2978

**Sierra National Forest**

1600 Tollhouse Road  
Clovis, CA 93612  
559-297-0706

**Six Rivers National Forest**

1330 Bayshore Way  
Eureka, CA 95501  
707-442-1721

**Stanislaus National Forest**

19777 Greenley Road  
Sonora, CA 95370  
209-532-3671

**Tahoe National Forest**

Highway 49 & Coyote Streets  
Nevada City, CA 95959  
530-265-4531

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